BEYOND ENERGY FUTURES:
AN EXPLORATION OF SUSTAINABILITY-DRIVEN AND
TRANSITION DYNAMICS-DRIVEN APPROACHES
TO GUIDING SOCIO-TECHNICAL CHANGE

by

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ABSTRACT

Energy technologies and systems are imperative for the proper functioning of our economies and societies, but due to their growing environmental and social impacts, there appears to be an interest in making a transition toward alternative forms of energy systems. However, making such a transition would involve understanding the complex characteristics of energy technologies, their interdependencies, sustainability impacts and socio-technical contexts, therefore, it calls for an inter-disciplinary approach to such an analysis.

This dissertation proposes two approaches to informing future energy and technology policies. The first approach is motivated by the need to improve methods for sustainability assessment. While a variety of tools and methods exist for the assessment of sustainability, there appears to be no systematic approach to their selection and thus the design of sustainability assessments is often driven by convenience, familiarity and availability of tools. Therefore, a framework (Sustainability Assessment Framework) is proposed for a more systematic approach to tool selection and for the design of the next generation of sustainability assessments.

The second approach is based on an attempt to understand the dynamics of technological transitions. Much of the literature on technological change focuses on technologies, but the technological transitions literature highlights the importance of thinking about transitions between socio-technical systems. This dissertation suggests that the guidance to socio-technical transitions may not come from choices made between technologies, but instead from choices made about desirable futures. The articulation of a desirable future may then enable compatible technologies currently within niches, to co-evolve and develop inter-dependencies with other compatible technologies and systems, thus initiating a possible socio-technical transition.

It is argued that both approaches complement each other in informing energy and technology policy regarding transitions to future energy systems. While the first approach (sustainability-driven) allows us to assess the sustainability of future technologies and systems, the second approach (transition dynamics-driven) informs us about the dynamics of the transition process and urges us to think of transitions in terms of a desired future and its characteristics (i.e. sustainability characteristics). Together the two approaches inform us on how we might think about choosing and guiding a desirable future.
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<tr>
<td>AFV</td>
<td>Alternative Fuel Vehicle</td>
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<tr>
<td>ANT</td>
<td>Actor-Network Theory</td>
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<td>BC</td>
<td>British Columbia</td>
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<tr>
<td>BCA</td>
<td>Benefit Cost Analysis</td>
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<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbines</td>
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<tr>
<td>CEA</td>
<td>Cost Effectiveness Analysis</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>CO$_2$(eq)</td>
<td>carbon dioxide equivalent with 100 year global warming potentials for carbon dioxide, methane and nitrous oxide of 1, 21 and 310 respectively.</td>
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<tr>
<td>CoSA</td>
<td>Comprehensive Sustainability Assessment</td>
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<tr>
<td>CUTE</td>
<td>Clean Urban Transport for Europe</td>
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<tr>
<td>DMFC</td>
<td>Direct Methanol Fuel Cell</td>
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<td>E2-models</td>
<td>Energy-Economy models</td>
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<td>E3-models</td>
<td>Energy-Economy-Environment models</td>
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<tr>
<td>EF</td>
<td>Ecological Footprint</td>
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<td>EV</td>
<td>Electric Vehicle</td>
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<tr>
<td>FCB</td>
<td>Fuel Cell Bus</td>
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<tr>
<td>FOSA</td>
<td>First-Order Sustainability Assessment</td>
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<tr>
<td>SOSA</td>
<td>Second-Order Sustainability Assessment</td>
</tr>
<tr>
<td>FCV</td>
<td>Fuel Cell Vehicle</td>
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<tr>
<td>HCNG</td>
<td>Hydrogen-enriched Compressed Natural Gas</td>
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<tr>
<td>IA</td>
<td>Integrated Assessment</td>
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<tr>
<td>IAM</td>
<td>Integrated Assessment Model</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
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<tr>
<td>ICEV</td>
<td>Internal Combustion Engine Vehicle</td>
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<tr>
<td>IFCI</td>
<td>Institute for Fuel Cell Innovation</td>
</tr>
<tr>
<td>IIASA</td>
<td>International Institute for Applied Systems Analysis</td>
</tr>
<tr>
<td>ISA</td>
<td>Integrated Sustainability Assessments</td>
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<tr>
<td>IPCC</td>
<td>The Intergovernmental Panel on Climate Change</td>
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<tr>
<td>IWHUP</td>
<td>Integrated Waste Hydrogen Utilization Project</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>LEED</td>
<td>Leadership in Energy and Environmental Design</td>
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<tr>
<td>L-SAP</td>
<td>Lead Sustainability Assessment Practitioner</td>
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<tr>
<td>LTS</td>
<td>Large Technical Systems Theory</td>
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<tr>
<td>MAT</td>
<td>Monetary Assessment Tools</td>
</tr>
<tr>
<td>MCA</td>
<td>Multi-Criteria Assessment (or Analysis)</td>
</tr>
<tr>
<td>MCFC</td>
<td>Molten Carbonate Fuel Cell</td>
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<tr>
<td>MFA</td>
<td>Material Flow Analysis</td>
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<tr>
<td>MLP</td>
<td>Multi Level Perspective</td>
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<tr>
<td>NAIDE</td>
<td>Novel Approach to Imprecise Assessment and Decision Environments</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NEB</td>
<td>National Energy Board</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
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<tr>
<td>NO$_x$</td>
<td>Nitrogen Oxides</td>
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NRC - National Research Council
PAT - Physical Assessment Tools
PD - Path-dependence
PIA - Participatory Integrated Assessment
PROMETHEE - Preference Ranking Organization Method for Enrichment Evaluations
PEMFC - Polymer Electrolyte Membrane Fuel Cell
PM - Particulate Matter
SAF - Sustainability Assessment Framework
SCOT - Social Construction of Technology
SD - Sustainable Development
SEA - Strategic Environmental Assessment
SIA - Sustainability Impact Assessment
SOx - Oxides of sulphur
SOFC - Solid Oxide Fuel Cell
ST - Socio-technical
STS - Science and Technology Studies
TC - Technological Change
TTDM - Technological Transitions and Diffusion Studies
TM - Transition Management
UBC - University of British Columbia
VA - Vulnerability Assessment
VFCVP - Vancouver Fuel Cell Vehicle Project
VOC - Volatile Organic Compounds
WEC - World Energy Council

UNITS

GJ - Giga Joule
kg - kilo gram
kW - kilo Watt
MW - Mega Watt
MWh_e - Mega Watt hour electric
MWh_t - Mega Watt hour thermal
Nm$^3$ - Normal cubic metre
TJ - Tera Joule
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Although completing a PhD is by no means a walk in the park, few would suggest that it is something you undertake all on your own. There are many who inadvertently become part of your journey, experiences, support network and contribute significantly without actually knowing it. While I have tried my best over the years to acknowledge and thank those who cared and supported this journey, there are always some who get left out. Therefore, I would like to take this opportunity to officially acknowledge all those who have played an important role in my life throughout this most amazing journey.

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To Mummy, Daddy and Lokutha

My only wish is that you were here today!
CO-AUTHORSHIP STATEMENT

While all of the research, data analysis and manuscript preparation within this dissertation was performed by Kirthi Roberts (author of this dissertation), two of my PhD committee members Prof. John B. Robinson (senior supervisor) as well as Prof. Walter Merida were important contributors to the identification and design of my research. As such they are co-authors of the manuscripts within this dissertation.
1 Introductory Chapter

1.1 Introduction

1.1.1 Organization of the Introductory Chapter
This chapter consists of four main sections. We begin with the problem context and the approaches within this dissertation that respond to that problem. This is followed by a description of the three main themes (or research spheres) of this dissertation and the motivation behind the inter-disciplinary approach to this dissertation. In section 1.2 the overarching research objectives will be provided and in section 1.3, I will then introduce and describe each of the chapters, as well as the chapter objectives, and how the chapters relate to each other. Section 1.4 forms the bulk of this chapter as it provides the literature review. There is no conclusion section for this chapter, but the chapter will end with a schematic (Figure 1-4) that represents the structure of the thesis.

1.1.2 The Problem Context

There is a growing understanding that for addressing today’s complex problems spanning multiple scales (spatially and temporally) and sectors, consisting of interactions between the sciences (both natural and social) and between science and policy, current research strategies, assessment methods and approaches to decision support may be inadequate. Therefore what may be needed for the policy process are integrated insights in contrast to the partial insights presently being offered based on today’s research tools and methods.

The actual conduct of a well defined research often found in disciplinary sciences is what scientists do best, however most problems that the public and policy makers face do not neatly present themselves within the confines of any particular discipline. Therefore,
disciplinary approaches to informing policy would reveal partial insights at best. Thus the collective challenge for natural and social scientists alike is in the design and conduct of inter-disciplinary research and the communication of research results to decision makers in policy relevant terms.

1.1.2.1 The Inter-disciplinary Approaches within the Dissertation

Given the significance of technology and energy systems to our economies and the growing concerns of their environmental and social impacts, there appears to be some interest in making a transition toward an energy future with lower environmental and social impacts. In order to provide integrated insights to informing energy and technology policy to this end, at least two inter-disciplinary approaches are conceivable. First, assuming that a transition toward sustainability is an over-arching policy goal, it would be important to gain insights into the sustainability of energy systems (for present and future systems). This I will refer to as the sustainability driven approach. Secondly, it is important to recognize that a salient characteristic of energy systems is that they operate on very long time-scales. In other words, transitions within energy systems happen over 5-10 decades. Such slow dynamics are the result of a complex web of interactions of energy systems with the economies, societies and cultural practices in which they are embedded. Given the long recorded history of energy systems and their transitions (over 2 centuries), a second approach to inform energy and technology policy may be possible, by taking a look back into past energy system changes as well as their dynamics of socio-technical change. This I will refer to as the transition-dynamics driven approach.
The two approaches do not compete with each other but are rather complementary to each other. Informing energy and technology policy, based only on insights from the assessment or application of sustainability principles to energy systems, without an appreciation or understanding of past energy system dynamics (and vice a versa) may be insufficient for sound policy-making. Thus a more complete analysis would include both approaches to informing policy. As will be seen in section in 1.2 and 1.3, the research undertaken within this dissertation attempts to explore these two approaches in order to gain insights about the sustainability of and transition to a future energy system.

1.1.3 The Three Research Spheres

The literature on Hydrogen Futures (and systems), Sustainability Assessment and Technological Change has largely developed and continues to develop almost independently of each other. However, if one wishes to think about the sustainability of hydrogen futures and the transition to such a future state from the present, then it may be necessary to explore the connections that might exist between these 3 areas, rather than study them in isolation. Therefore, what may be needed is a multi-disciplinary study exploring the dynamics of their interaction and application of their concepts across their boundaries, to facilitate such thinking. The research within this dissertation lies at the confluence of the above 3 fields of study, in order to improve our understanding about sustainability assessment and the dynamics of transition to a future energy system (see Figure 1-1).
The literature on hydrogen energy systems and hydrogen futures is not just about hydrogen but is also inclusive of the technology of Fuel Cells\(^1\). The various hydrogen feedstocks (including biomass, coal, natural gas etc.), production mechanisms, storage technologies, configurations (centralized/de-centralized), delivery modes (i.e. pipelines, trucks), the different fuel cell types in their various end-use applications all or any part of this larger hydrogen and fuel cell energy system in a future context is contained with the literature of hydrogen futures.

By Technological Change I am referring to the literature on the diffusion of individual technologies with and without substitution/replacement, to changes in large scale

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\(^1\) A Fuel Cell is an electro-chemical energy conversion device that can produce electricity (and heat) from hydrogen, typically in the presence of a catalyst.
technological systems, infrastructures and clusters of technologies. It also includes the societal context of technology, the transitions that may occur in socio-technical systems and ideas on how to manage transitions. This literature consists of numerous empirical studies as well as theoretical concepts and constructs about change processes within socio-technical systems. (The time scales of these processes may range from under a decade to centuries.) The literature on modelling technological change into energy-economy models will also be considered as inclusive of the Technological Change literature.

Although the theory and practice of assessments as well as the notion of sustainability are not new, the literature on the assessment of sustainability is relatively new. When referring to the field of sustainability assessment however, I am collectively referring to all assessment tools, assessment processes, ideas of integration between different assessment processes, and the integration of the notion of sustainability itself into the assessment process.

While the 3 different areas of study may be considered as the 3 pillars of my PhD research, it should be pointed out that Hydrogen Futures and its energy and technology context may be more appropriately considered as the medium through which the
application of sustainability assessment tools\(^2\) may be explored in the energy domain and through which technological change of past and future energy systems may be analyzed\(^3\).

1.1.4 Motivation for an Inter-disciplinary Approach

Given the complex nature of the problems we face and the limitations of today’s science, identified earlier,, a group of leading natural scientists, social scientists and policy analysts from around the world have proposed a new paradigm – *Sustainability Science* – to meet this challenge (Kates, Clark et al., 2001). The sustainability science that is necessary for this challenge has been described by the above group as being different from today’s scientific approach, in terms of its structure, methods and content.

Thus new methods and techniques are required to focus attention on the fundamental interactions between nature, society and societal artefacts (i.e. energy technologies, infrastructures and related systems) and to guide those interactions along more sustainable trajectories. To this end, seven core questions have been proposed for sustainability science by (Kates, Clark et al., 2001). These are shown in Box 1 below. Question 8 was an addition by (Swart, Raskin et al., 2004) who argue that scenario analysis is an important tool that can address many of the challenges of sustainability science and especially for scanning the future in a “structured, integrated and policy-relevant manner”.

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\(^2\) Throughout this dissertation the term ‘tool’ is used to refer to all tools, methods, methodologies and procedures that can be used to carry out an assessment or any part of it. This is the same definition used in the SustainabilityA-Test project discussed later.

\(^3\) In this sense ‘sustainability assessment’ and ‘technological change’ may be viewed as the two legs of ‘hydrogen futures’ and thus its position in Figure-1.
This dissertation to a large degree derives its motivation from this emerging sustainability science and in the process hopes to make a small contribution toward its further development. In particular, the objectives and research questions of chapters 2 and 3 are well aligned with CQSS-6 and CQSS-7 while those of chapter 4 are closely related to CQSS-1 and CQSS-2 and CQSS-8. Section 1.2 below provides the overarching research questions for this dissertation and section 1.3 discusses in more detail the particular objectives, research questions and methods of each chapter.

Box-1: Core Questions of Sustainability Science (Kates, Clark et al. 2001)

1. How can the dynamic interactions between nature and society – including lags and inertia – be better incorporated in emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?

2. How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?

3. What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?

4. Can scientifically meaningful “limits” or “boundaries” be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?

5. What systems of incentive structures – including markets, rules, norms and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?

6. How can today’s operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?

7. How can today’s relatively independent activities of research planning, monitoring, assessment and decision support be better integrated into systems for adaptive management and societal learning?

8. How can the future be scanned in a creative, rigorous and policy-relevant manner that reflects the normative character of sustainability and incorporates different perspectives?” (Question 8 added by (Swart, Raskin et al., 2004)

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4 The acronym CQSS will be used hereafter to refer to the Core Questions of Sustainability Science, while CQSS-n will represent a particular core research question, where n is an integer between 1 and 8.
1.2 Overarching Research Objectives

CQSS-6 refers to the need for improving today’s monitoring and reporting systems on environmental and social conditions to provide useful guidance in order to transition toward sustainability, while CQSS-7 is about the need to integrate monitoring, assessment and decision support for adaptive management and societal learning.

In relation to energy systems or energy-technology policy (the main context within this dissertation) part of this societal learning and guidance would come from improving the underlying methodology for sustainability assessments, which is presently under-developed. Among many challenges for sustainability assessment (both conceptual and practical), the process of selecting tools particularly seemed to lack any systematic approach. Admittedly, my attempt at a quantitative sustainability assessment of a real-life hydrogen energy scenario (topic of chapter 2) enhanced my own understanding of this problem.

Therefore, my first research objective is to:

- develop a framework, based on an understanding and analysis of the various tools available for sustainability assessment, for a systematic approach to the selection of tools.

CQSS-1 refers to the challenge of incorporating dynamic interactions and system wide intrinsic lag and inertia of nature-society systems into conceptual models of earth system, human development and sustainability, while CQSS-2 refers to the question of how long-
term trends in environment and human development re-shape nature-society interactions in ways relevant to sustainability.

Again it is possible to relate CQSS-1, CQSS-2 and the need to transition toward sustainability (CQSS-6) with the notion of transitions to future energy systems. In addition to the challenge of improving the methodology for sustainability assessment, (which does not have a temporal component) there looms the question about how transitions of energy systems come about, what are the conceptual and empirical models that explain the dynamics of transition, what are the dynamics of society-technology interaction and to what degree and how could be affect socio-technical change. While a variety of different literatures exist that tend to focus on these questions in isolation, the goal is therefore to explore this literature for integrated insights regarding how to affect socio-technical change.

Therefore, my second research objective is to:

- explore the theoretical and empirical literature on technical change in order to offer integrated insights about how to guide socio-technical transitions.

Together it is expected that meeting these two research objectives would take us closer to improving how we make choices about a sustainable future and how we might think about guiding a socio-technical transition toward such a goal.

1.3 Chapter Introductions, Objectives & Methods

Chapters 2, 3 and 4 form the bulk of the research contained within this dissertation. Hereafter, these will be referred to as the ‘main’ chapters. Chapters 2 and 3 follow the
sustainability driven approach while chapter 4 follows the transition-dynamics driven approach, described earlier.

1.3.1 Chapter 2: Characterization and Sustainability Assessment of Canada’s Hydrogen Highway

Chapter 2 is based on a case-study from Vancouver, British Columbia (BC) where with the financial support of the government (provincial and federal) and co-operation between government agencies, industry, local organizations and academia, a large scale demonstration project - British Columbia Hydrogen Highway project - is currently underway. This project is expected to be launched at the 2010 winter Olympics in Vancouver. The mission of the Hydrogen Highway project is to “enable and advance the use of Canadian hydrogen and fuel cell technologies” (Hydrogen Highway, 2007). In addition, according to (Connor, Britton et al., 2004) it intends to increase public and market awareness of hydrogen, fuel cell and related technologies during the 2010 Olympics, showcase the strengths and expertise of the BC hydrogen and fuel cells industry cluster and to have the world’s pre-eminent hydrogen economy by 2020.

The Hydrogen Highway consists of a network of individual nodes located across the lower-mainland of British Columbia, each consisting of projects such as hydrogen refuelling stations, waste hydrogen purification, hydrogen compression and distribution, hydrogen powered fuel cell vehicles, direct-hydrogen internal combustion vehicles, stationary fuel cells (generating power/heat and back-up power) as well as micro-fuel cell applications among others.
While much effort was directed toward the research and demonstration of individual projects and the promotion of a future hydrogen-based economy, upon examining the literature and based on direct communication with the relevant authorities, little to no effort seemed to be directed toward (a) the characterization of the entire Hydrogen Highway project or (b) the sustainability assessment of it.

The above realization was largely the motivation behind the research for this chapter. In addition, the following observations also provided support: (a) the sustainability of hydrogen and fuel cell systems seemed to be an implicit assumption in the literature (especially among scenarios promoting it) (b) there appeared to be no record of any attempts to conduct sustainability assessments elsewhere of even small-scale hydrogen and fuel cell based energy systems\(^5\) (and little evidence even for any other type of energy system) and (c) sustainability assessment itself was yet an emerging concept. Thus the objective of chapter 2 was to attempt to fill this gap in the literature linking hydrogen energy systems with sustainability assessment. In order to do that, a complete characterization of the Hydrogen Highway project was also conducted by developing a short-term (4 year) hydrogen energy scenario for BC (sections 2.3 and 2.4) which consisted of hydrogen production and consumption in British Columbia. The scenario was developed around the demonstration projects of the BC Hydrogen Highway project. Finally (in section 2.5), by utilizing a number of assessment tools, and based on the available information, a first-order or preliminary sustainability assessment was conducted.

\(^5\) This of course is a result of there being few hydrogen and fuel cell based systems existing worldwide combined with the fact that sustainability assessment itself is not standard practice any where.
In order to incorporate the lifecycle emissions and energy of the BC Hydrogen energy scenario, National Resource Canada's (NRCan) lifecycle emissions model, GHGenius 3.3, was used as the overarching framework. The GHGenius model is based on a life cycle analysis (LCA) framework. Nested within this LCA framework was the Cost-effectiveness Analysis (CEA) tool (based on the benefits of carbon reduction - cost per unit of green house gases saved).

The preliminary sustainability assessment attempted on the BC Hydrogen Highway, revealed some important insights regarding the limitations of such an assessment. In terms of the type of information that was available for the assessment, all of it was quantitative\(^6\) in nature. Since not all sustainability benefits are easily quantifiable, the importance of including qualitative data, as well as tools that are capable of accommodating both data types, was stressed. These results were important for the motivation of chapter 3. Also, while not dealt with explicitly, chapter 2 pointed to the importance of considering the dynamics of diffusion of technologies, infrastructures and their social context to inform future transitions.

1.3.2 Chapter 3: Sustainability Assessment Exposed – a framework for designing the next generation of assessments

The results from chapter 2 that had implications for chapter 3 may be summarized as follows: that not all sustainability benefits may be captured by any one tool (different tools are built for specific purposes), the importance of complementarity between tools, and the importance of assessment tools capable of accommodating quantitative and

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\(^6\) The corollary of this was not necessarily true, that all relevant quantitative information was available.
qualitative data, for sustainability assessment. Furthermore, upon examining the literature on assessments of energy systems (including hydrogen energy scenarios), it became clear that the process of tool selection for the assessments (sometimes called sustainability assessments) seemed to lack any systematic approach. Moreover, the tool selection seemed to be based on a somewhat arbitrary process influenced by availability, convenience or the assessor’s familiarity with a given tool (the tool selection in Chapter 2 was also subject to this same problem). With these issues in mind chapter 3 explores the methodological issues related to sustainability assessment and proposes a framework for tool selection to aid in the design of sustainability assessments.

Section 2 of chapter 3 (section 3.2) describes what sustainability assessment tools are, what has been said in the literature about them and how they have been combined in past sustainability assessments. This is followed by defining the universe of assessment tools that may be used for a given sustainability assessment, which is important for the development of the sustainability assessment framework in section 3.3.

In section 3.3 it is argued that all assessment tools may be classified into two levels: framework level and analytical level. A framework level tool while helping to define and characterize the problem provides the largest scope and flexibility for other tools to be nested within it. They also compensate for some of the methodological gaps that may lie outside the boundaries of the analytical tools used. For instance, in addition to highlighting the importance of the 3 pillars of sustainability (economic, ecological and socio-cultural), they try to capture some of the dynamics outside the 3 pillars by seeking
the gaps in our understanding, cross-cutting interactions between the 3 pillars, multiple stakeholder values, issues of scale, equity (inter-generational as well as intra-generational) etc. As such framework level tools cover a wide scope and consist of broad requirements, which as argued are necessary for designing a complex and non-trivial assessment process such as 'sustainability assessment'.

An important function of the framework level tool is also to help guide the selection of the analytical tools that are necessary for the sustainability assessment, through the process of characterization and problem definition. Thus, the tool selection process becomes the result of a more systematic approach, rather than an arbitrary process. Two framework level tools are identified from the universe of assessment tools as minimum conditions for the design of the sustainability assessment. They are the Integrated Assessment approach (IA approach) and the Multi-Criteria Assessment process (MCA process). As described in the chapter, the IA approach and the MCA process are based on the underlying philosophy to the widely used Integrated Assessment Models and Multi-Criteria Assessment Methods, respectively. Given the broad requirements mentioned previously for framework level tools, most other tools (with the possible exception of Scenario Analysis Tools or Stakeholder Analysis Tools) may be classified as non-framework level tools or analytical tools, because they tend to be more focused on a very specific function (based on a particular algorithm). Nevertheless they are an important contributor to the sustainability assessment process. However, it is their selection that is crucial based on the particular problem at hand. Therefore, the framework argues against
a one-size-fits-all approach and against an arbitrary tool selection process for sustainability assessment.

Section 3.4, we will delve into some of the main conceptual challenges associated with sustainability assessment, such as issues of scale, complexity, equity, problem framing, uncertainty, knowledge gaps etc. This will be followed (in section 3.5) by a discussion on the relevance of these conceptual challenges to the two levels of the sustainability assessment framework. As we will see many of the conceptual challenges need to be dealt with at the framework level as the scope of the analytical level is insufficient to address these challenges.

Ideally an Integrated Assessment would include stakeholder engagement, however, that is beyond the scope of chapter 3. However, in section 3.6 we will illustrate how even a preliminary and partial application of the framework level tools can help with the selection of the appropriate analytical tools for the analysis. This application will demonstrate that the selection of analytical level tools will be a result of a systematic and transparent process that emerges from the unique properties of the problem itself, and not by any arbitrary process of convenience, availability or familiarity. Section 3.7 will discuss some practical considerations for sustainability practitioners and close with the main conclusions from the chapter.
1.3.3 Chapter 4: Bridging the Gap – A Retrospective Analysis for guiding future Energy and Socio-Technical Change

As mentioned earlier chapters 2 and 3 were based on the *sustainability-driven* approach to informing energy and technology policy for future energy systems. However, given that chapters 2 and 3 do not explicitly consider the typically long time scales involved with energy systems, their transitions or their socio-technical context, it would be important to also inform energy and technology policy based on the transition dynamics of socio-technical change. To that end chapter 4 is based on *transition-dynamics driven* approach to informing policy.

Three large literatures exist (both empirical and theoretical) that may have direct implications for energy and technology policy related to energy system and socio-technical transitions. They are the literatures on socio-technical transitions, diffusion of systems of technologies and infrastructures and on the modelling of technical change. For purposes of brevity and easy reference this collective literature will be referred to as TTDM for Technological Transitions, Diffusion and Modelling. An analysis of the hydrogen futures literature revealed that while this literature discussed future hydrogen and fuel cell technologies, their diffusion and a possible transition to a future hydrogen economy, in probing the viability of such a future energy transition, it seldom made any connections to the three large literatures mentioned earlier. Chapter 4 attempts to bridge this gap in order to explore what the dynamics of past energy and technology transitions may tell us about future energy transitions.
While the hydrogen futures literature is used as a medium for the discussion of future energy transitions, chapter 4 does not attempt to answer the question of whether we should pursue a transition in the direction of a hydrogen energy future. Instead the objective is to explore the considerations that may be needed in order to think about future socio-technical transitions of energy systems. To this end TTDM literature is probed for patterns, mechanisms, lessons, etc., with the aim of improving our understanding of technology, its societal context and its diffusion and transition dynamics.

The notion of a future hydrogen energy system or a hydrogen economy, although used widely in the hydrogen futures literature, is not an idea that can easily be defined in unambiguous terms (McDowall & Eames, 2006a). Thus a brief discussion explains the origins of the ambiguity and provides a general idea of what it may entail (section 4.2). The heterogeneity of the various hydrogen production pathways (resulting from different hydrogen feedstocks, production and delivery mechanisms) tends to receive much attention in the hydrogen futures literature. Given that end-users are directly linked to the demand side (end-use fuel cells technologies in transportation, heat and power generation and portable electronics) and because different fuel cell types are (a) at different stages of development and (b) have different socio-economic and socio-technical criteria, these differences provide some important clues regarding the diffusion of end-use fuel cell technologies and systems. While this analysis of the demand side of a hydrogen energy system in section 4.2 is a small component of the chapter, its special characteristics stress the importance of explicitly considering the heterogeneous nature of the hydrogen
economy (supply and demand sides) if discussing or making policies toward a hydrogen future.

Section 4.3 of this chapter explores the three main components of TTDM literature for relevant insights that may be applicable to the discussion on future technological transitions. It also demonstrates the complexity of the technology diffusion and technological transition process as well as their socio-technical context. The goal in chapter 4 is to use these insights (from section 4.3) as building blocks in order to provide guidance for new ways of thinking about future transitions. While section 4.3 will be largely descriptive, connections are made to hydrogen and fuel cell energy systems and to the concept of socio-technical change throughout the section as appropriate.

Section 4.3.1 introduces the technological transitions literature and the Multi-Level-Perspective (MLP). The MLP is a theoretical construct that emerges from the transitions literature and consists of a nested hierarchy of 3 different socio-technical systems (ST-systems). Its purpose is to serve as a linguistic and conceptual aid throughout the chapter. The MLP and the ST-systems are described in detail in chapter 4. Section 4.3.1.1 then describes some transition dynamics of past technological systems and shows how it may be relevant to future energy system transitions, while section 4.3.1.2 discusses the regional differences in socio-technical systems that may complicate the transition process. Section 4.3.2 will discuss the literature on large-scale technical systems (LTS), the notion of technology lock-in, and the diffusion of infrastructures and technological clusters as they relate to socio-technical transitions. Finally in section 4.3.3 the main insights from the modelling of technical change in energy-economy models are discussed. Also, an
emerging sub-literature on the modeling of hydrogen futures will be explored for further insights as relevant to the discussion on the transition of energy systems.

In section 4.4, the main insights from section 4.3 are used to analyze energy technology policy across 3 temporal dimensions: past policy experience (section 4.4.1), present guidance for a hydrogen transition (section 4.4.2) and some thoughts on guiding socio-technical change (section 4.4.3). In section 4.4.1 some examples are given of past energy and technology forecasts that failed and policies informed by these forecasts. This section also suggests how the concept of choice is far more complex than is often represented and that there is a distinction between making a technology choice and making a choice about a desirable future. Section 4.4.2 demonstrates that in spite of the theoretical and empirical insights available from the TTDM literature (section 4.3) present guidance for a transition to a hydrogen future, is often plagued with simple models of technology diffusion and system transition. In section 4.4.3 while combining the insights from (a) diffusion of large scale infrastructures and technology clusters (b) recommendations from technology modeling literature (c) the multi-level perspective and (d) the concept of choice which emerged from analysis of past energy and technology forecasts, an alternative approach is suggested for thinking about transitions and for improving our chances to guide future energy system transitions. Section 4.5 closes with the chapter conclusions.
1.4 Literature Review

1.4.1 Thesis Format

Before starting the review of the background literature for this dissertation, it is important to first consider the particular format of this dissertation. The University of British Columbia (UBC) Faculty of Graduate Studies (FoGS) offers students two main formats for the submission of a written PhD dissertation. The “Traditional Thesis” format has been defined by FoGS as “a coherent document that provides a complete and systematic account of your research” (UBC Hydrogen Node Representatives, 2004). On the other hand the “Manuscript-based Thesis” format has been defined as one that is “constructed around one or more related manuscripts which have been previously published or which are being prepared for publication in an academic journal.” This dissertation is of the second kind.

1.4.1.1 Manuscripts and Journals

The manuscript for chapter 2 was accepted by the International Journal of Energy Research (IJER) in July 2006 and the publication is currently ‘in press’ ((Roberts & Robinson, 2007)). However, it is made available through Wiley InterScience as an ‘Early View’ on their online version of the journal.

Chapter 3 was submitted on Feb 16th to the International Journal of Sustainable Transportation (IJST), a publication of Taylor & Francis. Chapter 4 has been submitted to the journal of Energy Policy, a publication of Elsevier.
1.4.2 Organization of the Literature Review

It is important to note that the topics of hydrogen energy systems and of hydrogen futures are cross-cutting themes across all 3 chapters. Hence it makes sense to provide a separate review of it for all 3 chapters combined. While section 1.4.3 below provides a review of hydrogen energy systems and associated technologies, section 1.4.5.4 reviews the hydrogen futures literature within the context of guiding visions and technological expectations for socio-technical change. The theme of sustainability assessment is also cross-cutting across chapter 2 and 3, hence a separate review of this theme will be provided in section 1.4.4. Although technological change is a theme mostly relevant to chapter 4, a review of that literature will also follow in section 1.4.5.

Given the manuscript-based format of this dissertation, each chapter had to be a self-contained unit and thus contain some of the literature review as part of each manuscript. Given the length constraints for journals, the literature review in each manuscript will be more condensed in some areas and more detailed in other areas (as pertinent to the manuscript) than the review in sections 1.4.3, 1.4.4 and 1.4.5. The remainder of section 1.4.2 will briefly describe the literature reviewed within each manuscript and how it relates to the literature reviewed in sections 1.4.3 to 1.4.5.

Chapter 2: Chapter 2 consists of 2 main components: the BC Hydrogen Energy Scenario and the Sustainability Assessment of it. As the hydrogen energy scenario is developed in sections 3 and 4 of chapter 2, the various projects and actors of the BC Hydrogen Highway project are described in detail. Given that the inception of the Hydrogen Highway project was only as recently as 2004, the literature surrounding it is not very
extensive. Almost all the available literature including direct contact with the organizers was used in the construction of the hydrogen energy scenario in chapter 2. Thus a review of the BC Hydrogen Highway project will not be repeated here, but section 1.4.3 (review of Hydrogen Energy Systems) and section 1.4.5.4.1 (review of Hydrogen Futures) will serve as the general backdrop and literature review for this section.

The second component of chapter 2 was the application of Natural Resource Canada’s ‘GHGenius 3.3’ Model for the preliminary sustainability assessment. The chapter however does not contain much description of this model. While the details of this model will not be provided in this review (as they are not relevant to the overall discussion) the interested reader is referred to Appendix A.

Chapter 3: In chapter 3, the two main components are: the Sustainability Assessment Framework (SAF) and a preliminary application of it to an example from transportation - namely light-duty vehicles (including a variety of hydrogen fuel-cell vehicles). The main literature review for chapter 3 is provided in sections 1.4.3 (hydrogen energy systems), section 1.4.4 (conceptual challenges of sustainability assessment and sustainability assessment tools), section 1.4.5.4.1 (review of Hydrogen Futures) and section 1.3.6 (literature at the interface of Hydrogen Futures, Sustainability Assessment and Technical Change).

Chapter 4: As described earlier in section 1.3.3 of this chapter, chapter 4 consists of bridging the gap between 3 main literatures: socio-technical transitions, diffusion of systems of technologies and infrastructures and on the modelling of technical change). As
such, section 3 of chapter 4 (section 4.3) is separated into three sections providing a review of each of these three literatures. However, the exploration of those literatures was based on the main components from that literature relevant to the discussion of technological change and socio-technical transitions. A broader review of these literatures as well as a review of the hydrogen futures literature (in the context of guiding visions and technological expectations for socio-technical change) is given in section 1.4.5 in order to provide more context to chapter 4.

From this point onwards till the end of chapter 1, sections 1.4.3 to 1.4.6 will provide the literature review for the main chapters.

1.4.3 Hydrogen Energy Systems

While sustainability assessment methods, technological change and socio-technical transitions were the research focus in this dissertation, hydrogen energy futures and related systems were merely the medium for the research. As such detailed descriptions or review of this literature was not possible, particularly given the length requirements for journal manuscripts. To this end, this section discusses the main components of hydrogen energy systems and the worldwide activities underway toward the realization of future hydrogen energy systems. For a review of the broader hydrogen futures literature refer to section 1.4.5.4.1.

1.4.3.1 The Past

Hydrogen was discovered in 1766 by Henry Cavendish (Hoffmann, 2002), the first hydrogen-powered device – a balloon – made its first voyage in 1783 (Hoffmann, 2002),
and the Fuel Cell was invented by Sir William Grover\textsuperscript{7} in 1845 (Prohaska, 2001). However, it took about 120 years after its invention, before the first hydrogen-powered fuel cells were used in NASA’s Apollo and Gemini Space missions in the 1960s (Bellona Institute, 2002). While hydrogen was used for its lighter than air properties in air-ships by Europeans in the 1920s and 1930s, the live motion picture camera footage and live radio broadcast of Hindenburg accident in 1937 (Cadwallader & Herring, 1999) resulted in a major public outcry bringing an end to hydrogen airships (dirigibles) and perhaps much of the interest in hydrogen to a complete halt. As a guide to the long history of hydrogen and fuel cells Appendix-B provides the reader with a series of significant events (relevant to hydrogen and fuel cells) that have occurred over the past 230 odd years.

NASA’s massive engagement in the 1960s laid the groundwork for the renewal of the interest in the much forgotten fuel cell technology. Another boost for hydrogen and fuel cell technology occurred during the 1973-74 oil crisis. Incidentally, the first International Hydrogen Energy Conference (THEME\textsuperscript{8}) also took place during this oil crisis. One importing thing to emerge from this conference was the creation of the hydrogen movement, started by a group of scientists later referred to as the hydrogen romantics (Veziroglu, 2000). While the policy window for hydrogen seemed to have subsided with the oil prices in the 1980s more recently concerns over climate change, energy-security, local air-pollution etc., have re-invigorated the interest in a hydrogen based energy future.

\textsuperscript{7} While Grover himself called his invention the gas battery the term Fuel Cell was only coined about 50 years later in 1889, by a British scientist Ludwig Mond and his associate Charles Langer (Hoffman 2002).

\textsuperscript{8} The Hydrogen Economy Miami Energy Conference - THEME
In the next section we will take a look at what a hydrogen energy system may look like and how it might define a hydrogen future.

1.4.3.2 Components of a Hydrogen Energy System

A Hydrogen Energy System (HES) may consist of all the following supply side processes (and their respective technologies) such as: hydrogen production, storage, transport and distribution, and demand side technologies such as fuel cells in various end-use applications.

**Hydrogen Production**: Although hydrogen is the most abundant element in the universe it does not occur naturally and is often found bound to carbon in the form of hydrocarbon feedstocks (i.e. coal, natural gas) or to oxygen in the form of water (H₂O). Therefore the production of hydrogen (in its diatomic form H₂) requires a hydrogen rich feedstock and an energy source (the same feedstock or a secondary energy carrier such as electricity may be used) to extract the hydrogen from the feedstock. A number of processes exist for this purpose. Table 1-1 below provides a list of the different hydrogen feedstocks and hydrogen production processes. The particular technical details of the different production processes are not necessary for the discussion within this dissertation. However, Appendix-C provides additional information for the interested reader.
Hydrogen Feedstock | Production Processes
---|---
Coal | Coal Gasification
Biomass | Biomass Gasification (or other agricultural wastes)
Natural Gas (Methane) | Steam Methane Reforming (SMR)
Petroleum | Partial Oxidation of Hydrocarbons (POX)
Water | Electrolysis of Water
Algae | Biological Hydrogen Production

Table 1-1: Hydrogen Feedstocks and Production Processes.

**Hydrogen Storage:** Once the hydrogen has been produced there are a variety of hydrogen storage technologies available, such as compressed hydrogen, liquefied hydrogen, metal-hydride storage, under ground hydrogen storage as well storage in carbon-nanotubes or glass-microspheres. Each of these storage technologies is in a different stage of development and has its own techno-economic advantages and disadvantages. Again, the details of these hydrogen storage technologies are not important for this dissertation as we will not be operating at that level. For the interested reader however, Appendix-D provides additional information.

**System Configuration and Hydrogen Transport:** Two main architectures or configurations are available for hydrogen energy systems. They are the centralized configuration (central production) and the decentralized configuration (on-site production). The centralized configuration requires delivery of hydrogen through pipelines while the decentralized production requires little to no delivery. As one would expect, pipeline delivery is only cost-effective for large amounts of hydrogen, due to the high costs of the pipeline infrastructure. However, given the smaller demand for hydrogen likely in the early stages of a hydrogen economy, the de-centralized configuration is expected to be more suitable. If delivery of small amounts of hydrogen is
required in either configuration, hydrogen could be compressed or liquefied and transported by trucks.

While detailed calculations for infrastructure and final hydrogen delivery costs have been performed, for different hydrogen configurations under varying assumptions of hydrogen demand (Ogden, 1999b; Schoenung, Susan M., 2001; Schoenung, S. M., 2002), for the purposes of this dissertation these calculations and results will not be necessary.

The above was a brief overview of the supply side of hydrogen (also illustrated in Figure 1-2 at the end of this section). The demand side consists of a variety of different fuel cells which may be used in different end-use applications such as transportation, stationary power and portable power. The engineering design requirements (power, energy density, weight, temperature etc) for each of these applications are very different and as such they require the use of a variety of different fuel cells. Again while most of the technical details about these fuel cells are not important for the purposes of this dissertation, Table 1-2 provides a brief comparison of the different fuel cell types based on their application, fuel needs and efficiencies.
Each of the fuel cells in Table 1-2 is at a different stage of development. They also have different technical challenges as well as costs. As far as a hydrogen economy is concerned it is expected that these different fuel cells will largely replace their conventional counterparts in each of the application domains. However, the absolute cost of the fuel cell is a poor indicator of its ability to replace its competitors. The different fuel cells will have different barriers to diffusion based on their relative costs, total technology requirements for their implementation, as well as their ability to increase the performance and add new functionalities (these will be discussed in greater detail in section 2 of chapter 4). On the demand side an idealized hydrogen future is expected to consist of fuel cells powering all the different application domains within the various sectors of its economy. The supply side on the other hand will likely consist of some combination of primary energy sources and conversion technology for the production of hydrogen. Figure 1-2 and Figure 1-3 below provide an illustration of some of the fuel cell and hydrogen energy pathways possible for constructing hydrogen futures.

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9 The acronyms stand for, Polymer Electrolyte Membrane Fuel Cell (PEMFC), Direct Methanol Fuel Cell (DMFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC) and Alkaline Fuel Cell (AFC).

10 This refers to first law efficiency of converting the energy of hydrogen to electricity.

11 DMFC uses the same technology as in PEMFC but is designed to be used with methanol for very low-power applications (<100W).
Figure 1-2: Supply-side options for a possible hydrogen economy

Figure 1-3: Demand-side options for a possible hydrogen economy
1.4.3.3 Worldwide Initiatives toward a Hydrogen Economy

While there are many promoters and supporters of a future hydrogen economy (Dunn, 2001; Lovins, A. B., 1999; Ogden, 1999b) there are also some who are cautiously optimistic (European Wind Energy Association, 2003; National Research Council, 2004) or even skeptical about such a vision (David Suzuki Foundation & Pembina Institute, 2002; Eliasson & Bossel, 2003; Keith & Farrell, 2003; Suzuki, 2004b).

Nevertheless, it appears that the late 1990’s saw the emergence of a wave of unprecedented activity in the hydrogen and fuel cells arena worldwide. Of these, by far the most ambitious of goals for a future hydrogen economy was set by Japan, where the official forecast for the fuel cell market penetration is 50,000 FCVs and 2,100 MW for stationary fuel cells in 2010, and 5 million FCVs and 10,000 MW for stationary fuel cells in 2030 (Fukuda, K., Kobayashi et al., 2001). Much of this optimism is due to the large joint venture between the government, industry and academia that initiated a long-range (1993-2020) comprehensive plan, the WE-NET (World Energy Network) project, that aims for the worldwide deployment of hydrogen related technologies by the year 2030 (WE-NET, 2005). Another ambitious and unprecedented announcement came from Iceland in 1999, which proclaimed that it intends to become the world’s first hydrogen economy by 2030 (Árnason & Sigfússon, 2000; Dunn, 2001). Many other countries have since followed suit by initiating and implementing hydrogen R&D activities and demonstration programs. For instance several states in the U.S.A such as California, Michigan, Hawaii and Ohio are actively working on making hydrogen and fuel cells a significant part of their energy future. Significant funds have been proposed nation wide
to further enhance these activities. Government Schwarzenegger’s Executive order (State of California, 2004) and President Bush’s FreedomCAR and FreedomFUEL initiative stand as major political support behind this movement (US DOE, 2005b).

Other followers in Europe are Germany, Norway, and the EU as a collective. Germany, according to (Bünger, 2001) has been through 3 phases of hydrogen development activities since the 1970’s. Among the current activities the Transport Energy Strategy (TES), a collaboration among 4 German automobile companies (BMW, Daimler-Chrysler, MAN heavy duty vehicles and Volkswagen) and 3 energy companies (ARAL, RWE and Shell) on hydrogen as an alternative fuel is among the most important in the country. Norway is also taking the hydrogen challenge seriously by initiating a “Hydrogen Highway” to be built between Oslo and Stavanger (Bak, 2003). The EU as a collective has also taken serious steps towards the implementation of a hydrogen and fuel cell energy policy (European Commission, 2005) and practical demonstrations such as the CUTE (Clean Urban Transport for Europe) project (CUTE, 2003).

Even some developing countries with large markets such as Brazil, China and India have jumped on the hydrogen and fuel cell bandwagon, implementing their own hydrogen energy programs mainly in transportation applications (Schettino, 2002) (Cropper, 2002a, 2002b; Dutta, 2004). Both India and China are also two of five countries that have received funding from the Global Environment Facility (GEF) - a unit of the United Nations Development Programme (UNDP) - for cutting local air-pollution and global
GHG emissions through the implementation of fuel cell technologies (Cropper, 2002a, 2002b).

In addition to the various country initiatives mentioned above, there is also an international effort undertaken with the formation of the IPHE (International Partnership for the Hydrogen Economy) in 2003 (US DOE, 2003a). The 17 countries that currently comprise the IPHE are responsible for 85% of global GDP, encompasses a population of 3.5 billion, and are responsible for about two-thirds of global energy consumption and CO₂ emissions (IPHE, 2005). The IPHE partners anticipate that by coordinating efforts they would be able to leverage international RD&D funds and reduce costs of hydrogen and fuel cell research programs in their respective countries through information sharing. In addition, the IPHE provides a forum for advancing policies and informing stakeholders and the general public on the benefits and challenges of establishing a hydrogen economy.

All of the above activities have been in effect for less than a decade. Although it may appear that internationally there is much activity to promote the vision of a hydrogen energy future, it is important to recognize that the level of investment for these programs is very small compared to the investments that typically go into the maintenance and development of current fossil based energy technologies and systems. Given the short time of the above activities and the levels of investment, neither hydrogen nor fuel cells have made any noticeable contribution in the secondary energy mix or end-use applications of any country. In this regard, while analyzing the sustainability of the BC
Hydrogen Highway and the hydrogen energy scenario, chapter 2 points to the apparent disjuncture between the hydrogen activities and the existing energy system in 2010. And in terms of timescales for transitions chapter 4 discusses the long time frames involved as well as the complex dynamics in the transition to a future energy system. As such the flurry of activity in hydrogen and fuel cells while important for its realization, at the present may be considered to be relatively small, in terms of larger investments of current energy systems and in terms of the very long time-scales for transition.

1.4.3.4 The Desirability of a Hydrogen Energy Economy

A number of reasons may be given for the desirability of a hydrogen future. Some refer to the decarbonization\(^{12}\) trend of global energy systems pointing to a hydrogen future (Barreto, Makihiro et al., 2002), while others point to the shift from solid (wood and coal) to liquid (petroleum) to gaseous fuels (natural gas) and hence hydrogen gas (Hefner III, 2002). The increasing hydrogen content (increasing hydrogen to carbon ratio) in each of these fuels is also what some believe leads us to a hydrogen energy future.

Since the use of hydrogen in fuel cells result only in water vapour and heat, with no greenhouse gases or other pollutants or emissions (hydrogen combustion also results in low emissions) this characteristic alone presents wide desirability. However, because hydrogen does not occur naturally, the upstream emissions from the hydrogen production process must be considered explicitly in order to assess the overall emissions. Another desirable feature is the fact that hydrogen may be produced from a variety of different

\(^{12}\) Decarbonization is a trend towards overall reduction in carbon intensity, where carbon intensity is the amount of carbon released into the atmosphere per unit of energy used.
energy sources or feedstocks (Table 1-1), thereby improving the energy security of a given energy system (Ogden, 1999b). Furthermore, some of hydrogen's physical and chemical properties also make it a safer fuel in certain respects\(^{13}\) (Veziroglu, 2001).

Fuel Cells on the other hand have the advantage of providing power with no requirement to recharge, so long as hydrogen (or its particular input fuel) is available. In addition, due to their modularity, fuel cells can generate much higher levels of power than batteries. As there are very few moving parts, fuel cells also have the advantage of quiet operation.

As such in certain aspects, hydrogen and fuel cells appear to have a number of desirable characteristics. However, they both also have a number of disadvantages such as the potential to generate emissions upstream, some undesirable chemical and physical properties, high costs of production and high material and energy intensities (for hydrogen and fuel cells) to name just a few. As such the benefits of a hydrogen future are not necessarily straightforward. Given that hydrogen and fuel cells have never been part of our energy systems and given that the notion of sustainability is relatively new, few tools or methods exist to assess the sustainability of future hydrogen energy systems with their fossil based fuels and technologies. Chapter 3 in this regard proposes a framework in order to contribute to the design of sustainability assessments of such desired futures.

Section 1.4.3 is relevant to all chapters; the review in section 1.4.4 is for chapters 2 and 3.

\(^{13}\) For instance hydrogen's faster diffusion rate in air, high specific heat capacity and ignition temperature, lower explosion energy and flame emissivity, are all highly desirable characteristics for a fuel. However, its very wide flammability limits in air, low ignition energy in air, as well as it being odourless and colourless are all less desirable characteristics as far as safety is concerned.
1.4.4 Sustainable Development and Sustainability Assessment

Although the term sustainable development will hardly be used in this dissertation, sustainability assessment may be thought of as the next generation of assessment practice, influenced by the notion of sustainable development. As such, we will discuss the concept, its origins and its duality in section 1.4.4.1. Section 1.4.4.2 will then explore some of the conceptual challenges associated with sustainability assessment and finally in section 1.4.4.3 we will review various assessment tools that may be used for sustainability assessment. Many of the themes and ideas discussed in these sections will form important building blocks for chapters 2 and 3.

1.4.4.1 Sustainable Development

The concept of sustainable development (SD) became known to the wider population through “Our Common Future” (commonly known as the Brundtland Report) - the report of the World Commission on Environment and Development (Brundtland, 1987). However, the roots of this concept may be traced far back in history. The Inuit saying, ‘we do not inherit the Earth from our parents; we borrow it from our children’ and the Native American ‘Law of the Seventh Generation’ are two illustrations of its long unrecorded tradition (Mehra, 1997). A detailed account of the more recent history of SD is given in (Robinson, J., 2004). According to Robinson the concept of SD is a logical extension of the arguments within the environmental literature of the 1960s, 70s and early 80s, which in turn date back to the conservation/preservation debate of the late 19th century.

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14 Robinson argues that one’s interpretation of SD depends on their position on the conservation-preservation spectrum.
Rachel Carson’s *Silent Spring* and Hardin’s *Tragedy of the Commons* in the 1960s, Meadows’ *Limits to Growth* in the 70s, IUCN/UNEP/WWF’s *World Conservation Strategy*\(^{15}\) of 1980s were the precursors to the Brundtland Report of 1987. These early concerns about the impacts of human activity on the environment, fears approaching the earth’s carrying capacity and the importance of the need to stay within its limits are at the core of the message in the Brundtland Report.

1.4.4.1.1 *To Define or not to Define*
While the Brundtland Report’s definition for SD is the most popular and widely quoted, it has also generated some intense debate surrounding its meaning.

> “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” –(Brundtland, 1987)

The most popular critique is that it is not clear from the definition what is meant by the term development, how it should be measured, how far into the future one needs to consider the needs of the future generations and what these needs might be. Therefore, the difficulty in projecting needs into the future without knowing exactly the socio-technical transitions (topic of chapter 4) of our successors is daunting at best. Perhaps in response to such dilemmas, Daly argues that the future will be at least well off as the present, in terms of its access to biophysical resources and services supplied by the ecosystem, if the natural capital\(^{16}\) is kept intact (Daly, 1996, 2002).

\(^{15}\) The acronyms are International Union of Concerned Scientists (IUCN), United Nations Environment Programme (UNEP) and World Wildlife Fund (WWF).
\(^{16}\) By natural capital he is referring to the capacity of the ecosystem to yield both a flow of natural resources and a flux of natural services.
The concept of natural capital has led to a bifurcation of the idea of sustainability into what is called strong sustainability and weak sustainability (Gutes, 1996; Pearce & Atkinson, 1993). Strong and weak sustainability both assume the importance of maintaining the total capital (natural capital + manmade capital). However, weak sustainability assumes the substitutability of manmade capital for natural capital while the concept of strong sustainability rejects the idea of substitutability of these two forms of capital for each other, and argues that they are complements instead. Some support the former (Board on Sustainable Development, 1999) while others support the latter (Daly, 1996). Although Daly is a supporter of the strong sustainability paradigm, he concedes that even weak sustainability would be better than current practice.

It is worth pointing out that Daly further emphasizes the distinction between “sustainable growth” and “sustainable development”. He says that the former implies an eventual impossibility because any economy is a sub-system of a finite and non-growing earth. Therefore he argues that it is development that can have the attribute of sustainability, not growth17 (Daly, 1996). According to Daly, what is to be sustained is a level, not a rate of growth, of physical resource use and what is to be developed is the qualitative capacity to convert that constant level of physical resource use (throughput) into improved services for satisfying human wants (Daly, 1990, 2002).

While the definition of the Brundtland Report is the most commonly cited, there are hundreds of other definitions for sustainable development (Murcott, 1997). Some stress

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17 In economic terms, Daly defines development as more utility per unit of throughput and growth as more throughput; he criticizes current economic theory for defining development as growth, in GDP.
the importance of clarity in order to make progress (Mehra, 1997) while others accept the
vagueness and believe it to be beneficial in the messy world of politics and policies,
perhaps even representing a political opportunity (Robinson 2004). In addition, some
believe that the very vagueness lends itself to the popularity of the notion (Daly 1990).
Daly even commends the Brundtland commission for not foreclosing this vagueness by
insisting on a precise analytical definition. He argues that we do not have a precise
definition of ‘money’ or ‘income’ and yet we could not do without them and urges those
impatient with this vagueness not to expect analytical precision when reasoning with
dialectical concepts (Daly 1990).

1.4.4.1.2 The Duality
Despite the multiplicity of definitions, interpretations and ideas on this concept, it is
important to note that some commonalities exist. A common approach to think about
sustainable development has been to think of it in terms of its three pillars or dimensions
– environment, society and economy – and the interactions between them. Others have
added the institutional dimension as a fourth category (Pinter, Hardi et al., 2005). A
similar approach is to think of it in terms of the interaction between humans and nature.
There is also a general consensus on the importance of intra-generational and inter-
genерational equity (UNCED, 1992). As argued in chapter 3, one may conceive of the
sustainability assessment process as consisting of a duality (Gibson, Hassan et al., 2005).
While it is important to integrate the most common ideas and values of SD mentioned
above, there are also context specific values, criteria, objectives and concerns. This
duality will be important for the development of the sustainability assessment framework
in chapter 3.
A somewhat interesting outcome of the debate around SD is that most like the idea, without necessarily knowing what it means. Perhaps this is so because sustainable development sounds better than unsustainable non-development (Daly, 1996). While the most intense debates on this issue seem to occur in the social sciences and politics, in scientific circles (hard sciences), perhaps due to the intrinsic vagueness, the discussion around it is less obvious. The research contributions of chapters 2 and 3 (sustainability assessment of hydrogen futures) intend to go some way in extending this discussion into the harder scientific realms.

1.4.4.2 Sustainability Assessment – Conceptual Challenges

So far in section 1.4.4 we discussed the concept of Sustainable Development its origins and some of the conceptual problems associated with it. A major component of chapters 2 and especially chapter 3 however, deal with the assessment of sustainability. Not surprisingly, it too is associated with some key underlying conceptual challenges, such as issues of complexity, problem framing, incommensurability, uncertainty, gaps in our knowledge, inter/intra-generational equity and issues of scale. In this section we will explore these conceptual challenges associated with sustainability assessment, as they will form important building blocks for chapter 3 in particular. The discussion below will focus separately on each of these issues, it should be noted that they are not necessarily independent from each other.

Complexity: Complexity manifests itself in sustainability assessments in two important ways. Firstly, through the multiplicity of views and differing societal values regarding
sustainability itself as discussed earlier, and secondly through the complexity of the systems being evaluated. Most real world systems and problems may be considered as being complex and according to (Funtowicz, S., Martinez-Alier et al., 1999; Rosen, 1977) when the relevant aspects of a given problem cannot be captured by a single perspective, it may be considered as being a complex system. The discussion of hydrogen energy systems in chapters 2 and 3 in particular will demonstrate its complex characteristics and the challenges associated with the discussion of its sustainability.

**Ceteris Paribus:** This is the Latin term generally used in economics to mean “all else being equal”. When comparisons are made in complex systems, often there is a possibility to make ceteris paribus type fallacies, if all else is assumed to be equal when it is not. For instance, as we will discuss in chapter 3, often assessments between different vehicles ignore the ‘vehicle manufacture stage’ since it consumes only 10% of the total life-cycle energy of a vehicle. However, not all impacts are scaled accordingly; life-cycle toxic chemical release for instance, which is more directly related to human health impacts, is 60% for the vehicle manufacture stage (Maclean, Heather L. & Lave, 1998). As such ignoring the vehicle manufacture stage based on its proportion of energy consumption, would inadvertently conceal important information relevant to the sustainability assessment.

**Problem Framing:** How the problem is framed is critical to the sustainability assessment. However, depending on the level of rigour applied to a given assessment and the likelihood of different and contested framings, the sustainability assessment may vary
greatly. Contested problem framing is an outcome of the multiplicity of values and viewpoints on any particular problem. This problem is most obvious during the stakeholder engagement process, and therefore the challenge for the practitioner is to incorporate as many aspects of the different problem framings as possible and arrive at an agreeable framing of the problem. While most tools are well equipped to deal with very specific analytical functions, few tools are capable of dealing with this problem (i.e. scenario analysis, stakeholder engagement, integrated assessment). This distinction between tools in their ability to perform analytical functions or deal with broader sustainability concerns will form an important building block for the development of the sustainability assessment framework.

**Incommensurability:** This is also an outcome of the complexity associated with the concept of sustainability. Given the multi-faceted and multi-dimensional nature of it, each and every measurable parameter or impact will be measured in units that are likely to be incommensurable with at least some of the other parameters. Furthermore, not all aspects and values embedded within the notion of sustainability are easily measurable or quantifiable, further complicating the issue of commensurability. A number of authors have argued against attempts to reduce incommensurable parameters in assessment processes and proposed a multi-criteria assessment (MCA) framework as an appropriate policy-framework when faced with incommensurability (Giampietro, Mario, Mayumi et al., 2006; Munda, 2005). Given the certainty of incommensurability in sustainability assessments, as we will see in chapter 3 MCA will be an important part of the proposed sustainability assessment framework.
The concept of incommensurability has been further separated into social incommensurability and technical incommensurability in the literature (Munda, 2004) – the former referring to the multiplicity of legitimate values in society and the latter to the possibility of multiple representations and identities of a system in descriptive models. These ideas relate directly to the discussion on complexity earlier.

**Uncertainty:** Uncertainty is an inescapable reality in most complex technical, social and socio-technical systems as well as an inherent feature of the future. Therefore, it is no surprise that it too is an important challenge for sustainability assessments. Given its universality much has been written about it in a variety of literatures: ranging from sustainability science (Swart, Raskin et al., 2004), post-normal science (Funtowicz, S., Martinez-Alier et al., 1999), climate science (Mori, 2006), modeling technical change (Gritsevskyi & Nakicenovic, 2000), to name just a few.

A related problem with uncertainty is how it is reported and communicated by scientists in different disciplines. Given the multi-disciplinarity of sustainability this can also pose a problem for sustainability assessments. There is also no widely accepted typology or characterization of it. According to (Kann & Weyant, 2000) there are 2 main types of uncertainty: parametric uncertainty (due to imperfect knowledge) and stochastic uncertainty (due to natural variability). A somewhat broader typology is used to guide the discussion and reporting of uncertainty in the Intergovernmental Panel on Climate Change (IPCC). Here uncertainty is characterized with a three-fold typology based on –
unpredictability, structural uncertainty and value uncertainty (Manning, 2006). The first dimension is based on examples of unpredictability of human behaviour and chaos in complex systems; structural uncertainty refers to competing conceptual models and the lack of agreement on their structure, modeled relationships, boundaries and definitions; and finally value uncertainty is based on missing or non-representative data, poorly known or changing model parameters etc.

In sustainability assessment uncertainty arises due to all of the reasons mentioned above. Due to the incomplete state of knowledge often assumptions need to be made on key parameters. The sustainability assessment of the BC Hydrogen Highway in chapter 2 clearly states all the underlying assumptions that were used in constructing the 2010 hydrogen energy scenario for BC and discusses their consequences at the end of the chapter. The discussion of future hydrogen energy systems as a whole is filled with references to uncertainty as there are more questions than answers about the configurations of hydrogen systems (centralized/decentralized), hydrogen production methods and their costs, demand for future hydrogen technologies and their costs, and of course their sustainability.

In terms of sustainability assessment tools, some are better equipped to deal with uncertainty than others. For instance, the tool ‘scenario analyses’ was developed to capture the uncertainty of the future through different scenarios – alternative images of how the future might unfold (Nakicenovic, N, Alcamo et al., 2000). Integrated Assessment also emphasizes the need to deal with uncertainty more explicitly (Morgan,
G. & Dowlatabadi, 1996). Similarly multi-criteria analysis (MCA) encourages the inclusion of multiple criteria in order to capture a more balanced picture of the problem being assessed. In chapters 2 and 3 we will discuss in more specific terms the role of uncertainty in sustainability assessments.

Knowledge Gaps: A major problem with many assessments is ignoring or not even acknowledging the gaps in the knowledge relevant to the assessment. This is especially true with assessments which are more quantitative in nature. While it is not possible to quantify the unknown, not even acknowledging how those gaps may relate to what is known, may give a false sense of confidence to the results of the assessment and prevent the actual inclusion of that information in the future when more is known. Thus ignoring parts of the problem poorly understood or not understood at all may not be justifiable for sustainability assessments. Integrated Assessment in particular stresses the importance of not ignoring poorly understood parts of the problem. Commenting on attributes of a good IA in the context of climate change, (Morgan, G. & Dowlatabadi, 1996) suggest that

"Parts of the problem about which we have little knowledge must not be ignored. Order-of-magnitude analysis, bounding analysis, and carefully elicited expert judgment should be used when formal models are not possible".

As we will see in chapters 2 and 3 considerable knowledge gaps exist in the respective problems chosen for assessment. For instance in chapter 3 significant data gaps existed in the scenario construction process. However, as mentioned earlier assumptions were made where information was unavailable and sensitivity analysis conducted where necessary.
However, gaps in knowledge may not always be simply remedied with assumptions and sensitivity analyses. As discussed in chapter 3 the science of local air pollution and the understanding of the health impacts of pollution, while having made significant progress in recent years, is still far from complete. In this case it is much harder to make simplified assumptions or sensitivity analysis as some of the causal mechanisms relating to air pollution and its human health impacts are still unclear. While representation of knowledge gaps in the assessment is clearly challenging, they should be discussed at least qualitatively so that when the information becomes available they may be included more formally into the assessment. Also, their identification will further help expand research in that direction and increase our chances of bridging that gap, and navigating toward a more sustainable future.

**Inter/Intra generational equity:** The Brundtland Commission’s definition of sustainable development makes clear the importance of inter-generational equity (Brundtland, 1987) – which is based on equity over time. Similarly it is important to consider equity across space – intra-generational equity. The common challenge however, is that there is no common metric or method for measuring equity. However, equity may be viewed in terms of the population or group receiving benefits or impacts of a certain action. For instance, since green house gas (GHG) emissions and their climate change impacts are felt over longer time-frames (and also across larger geographical regions) than local air-pollution impacts, identification of the groups affected would be a first step in the incorporation of equity into the assessment. While different stakeholder groups and
members within a group would value equity issues differently, it also poses a challenge of integrating their concerns in an agreeable manner into the assessment.

**Integration across Scales:** Issues of scale are also an important consideration for sustainability assessment. As discussed above, intergenerational equity operates on the temporal scale while intra-generational equity operates on the geographical scale. Also within these scales different studies may choose smaller or larger geographical-scales and time-scales for their analyses.

Scale is also important from the point of view of the different time-scales associated with different processes. For instance, impacts of ozone on human health take place on the order of hours/days, while GHGs can stay in the upper atmosphere for a few centuries and can cause impacts long after they have been emitted.

Using hierarchy theory to analyze the concept of sustainable development (Giampietro, Mario, 1994) discusses how the chosen scale of analysis can cause a discrepancy in the values and perspective even when assessing the same phenomena or action. Thus, if results from other studies are to be incorporated into a sustainability assessment, it is important to consider the relevant scales used and their suitability for the assessment.

Scale may also be considered from a sectoral perspective. For instance different studies may choose to focus on different sectors of the economy for their assessments. (Rotmans, J., 2004a) is critical of present national and international policy processes which are largely based on sectoral assessments, as they fail to achieve broader sustainability
targets. Hence he proposes a cross-sectoral approach to sustainability assessment. While this may be preferable at a higher-level, focused assessments are sometimes necessary and justified so long as caution is exercised when generalizing results.

1.4.4.3 Sustainability Assessment Tools

A variety of different assessment tools have been developed over the years for the assessment of environmental impact, life cycle impacts, costs and benefits etc. These assessment tools were developed over the years independent of each other in separate disciplines and while capturing important components of sustainability they tend to have systemic biases leaving out other important sustainability aspects. Also their treatment and emphasis of quantitative and qualitative data is often different.

Some examples of such assessment tools are Cost-Benefit Analysis (CBA) or Cost-Effectiveness Analysis (CEA) used primarily for monetary assessments and Life Cycle Analysis (LCA) and Material Flow analysis (MFA) used for ecological assessments. The most common tools used in the assessment of hydrogen and fuel cell systems are Life Cycle Analysis (Maclean, Heather L. & Lave, 2003; Spath & Mann, 2001; Wagner, Geiger et al., 1998), Scenario Analysis (Fukuda, K., Kobayashi et al., 2001; Sorensen, Hauge Petersen et al., 2004) and Multi Criteria Analysis (Afgan & Carvalho, 2004; Raugei, Bargigli et al., 2005).

1.4.4.3.1 The Sustainability A-Test

There are also dozens of other tools used to assess various aspects of sustainability for a variety of different problems. However, since the assessment of sustainability would
likely incorporate the integration of a variety of tools it would be convenient to be able to evaluate and compare this universe of tools in a consistent manner within a common framework. To this end, in 2005 the European Commission undertook one of its most comprehensive research projects, *Sustainability-A Test*\(^\text{18}\), which is an evaluation of the methods and techniques that may be used for sustainability assessment in support of policy-making (de Ridder, 2005a). While *Sustainability-A Test* provides an excellent resource for the practitioner of sustainability, how one should select between these tools was not within its scope. This is the topic of chapter 3.

An outcome of the *Sustainability-A Test* project is the development of a sustainability ‘toolbox’ consisting of about 50 different assessment methods and techniques separated into eight broad families. Table 3-1 (chapter 3) provides a detailed list of all the tools evaluated within the different families. Therefore it will not be repeated here. Also, a review of 50+ tools is not practical nor is it necessary for the development of the *Sustainability Assessment Framework* in chapter 3. However, a brief overview of the 7 tool families is provided below.

Physical Assessment Tools measure the impact on the environment due to human activities. In doing so, they tend to rely upon physical data concerning the consumption of natural resources. One weakness may be the accuracy of the measured physical quantity in terms of capturing the actual impact. Monetary Assessment Tools are based on the monetization of all impacts so that the different impacts may be compared with one another. A general

\(^{18}\) *Sustainability-A Test* stands for *Sustainability Advanced Test*. 
weakness of this tool is that not everything is monetizable and even if it were the assumptions behind the monetization are not universally accepted.

Modeling tools tend to use computer models to structure scientific thinking in a multi-disciplinary setting. While attempting to capture the most relevant processes they tend to focus on making predictions about the system under question, and its responses. SustainabilityA-Test classifies all modeling tools into 3 categories based on their levels of thematic integration: bio-physical models, socio-economic models and integrated models. The main criticisms against these modeling tools are the simplifications often made within the model in order to represent reality. Also the design and structure of the model is also given as reasons for systemically predetermining the outcome (de Ridder, 2005).

Scenarios Analysis tools generally are based on developing scenarios in order to explore the consequences of a range of assumptions and driving forces. They generally tend to include quantitative as well as qualitative data and may utilize graphs, charts, table and text in order to develop the scenarios. The development of scenarios that are internally consistent tends to be a time consuming process. While scenario analysis allows the inclusion of quantitative and qualitative information given the lack of standards for scenario developments it is important to be transparent about the different assumptions and the reasons for their inclusion.

SustainabilityA-Test includes 7 different methods under the family of Multi-Criteria Assessment. While part of the process is common to all the seven methods, they differ based on their assumptions about compensability (aggregation and thus compensation for the performance of the poor performance of one criterion by the better
performance of another) of the various criteria, which are often considered under a multi-
criteria process. While those that allow compensation reflect the weak sustainability
approach, those that don’t belong to the strong sustainability approach, and those that
allow partial compensation are in between (de Ridder, 2005; Munda, 2005). Generally all
MCA methods tend to incorporate different algorithms in order to rank the different
alternatives. A common criticism is that the rankings are dependent on the method used
and ranks may be reversed depending on the options considered.

Sustainability Appraisal Tools are considered as strategic decision support tools
that can contain multiple tools and methods and as such are generally wider in scope.
These tools are also closely connected to the general sustainability principles (i.e. 3
pillars model) Due to their flexibility and connection to the decision support tool these
tools are considered a bridge between other tools and the policy process (de Ridder,
2005).

Stakeholder Analysis Tools are necessary in order to incorporate the values,
knowledge and concerns of the public and stakeholders in the decision making process.
As such these tools tend to be interactive in nature. These tools also tend to enhance
creativity and social learning among the participants (de Ridder, 2005; Tansey,
Carmichael et al., 2002).

This concludes the review of sustainability assessment - the topic mainly of chapters 2
and 3. Next, we turn to the literature review on Technical Change, mainly relevant to
Chapter 4.
1.4.5 Technological Change – from technologies to ST-systems

At the most basic level, technological change may be described as a direct consequence of innovation in technologies and technological systems. However, the concept of innovation may be defined as narrowly or as broadly as necessary depending on one’s focus. It will be shown that while it is possible to discuss innovation and technical change from the level of particular technologies, adopter groups or firms, the notion of technological transitions requires the discussion to occur at a much higher level – at the level of systems of technologies or socio-technical systems (ST-systems).

Although the discussion in chapter 4 occurs at the level of ST-systems, the review below will first explore important concepts related to the innovation and diffusion at the level of technologies and technical systems. In particular, we will first explore this literature in a number of different directions, i.e. the various typologies of innovation, Large Technical Systems, co-evolution of technology, long-wave theories and technological clusters. This will be followed by an exploration of some of the building blocks that will be used in chapter 4 through an exploration of the literature on socio-technical transitions (transitions theory). The latter part of this section will focus on a review of the literature on hydrogen futures and the role of guiding visions and expectations in shaping it.

1.4.5.1 Typologies of Innovation and Technical Change

Innovation studies cannot be defined as a unified field of study, as it is an evolving and inter-disciplinary field at the cross-roads of sociology, technology studies (including history of technologies), economics, psychology and policy studies. However, according to (Smits, 2002) there are 2 major approaches to innovation studies: the analysis of
innovation based on innovation processes and its various actors and the analysis of innovation based on a systems perspective (institutions, structures, systems). The former is based on the conceptualization that “innovation is a process in which the generation of variations and making choices alternate” and the latter on the idea that the success of innovation processes is determined mainly by the level of co-ordination of organizations able to influence the course of innovation processes. As (Smits, 2002) points out it is this structure of the innovation system that determines its character and behaviour in terms of transitions, path dependencies or system inertia.

While these 2 approaches provide a simple demarcation of innovation studies, the richness of this field may be better captured by the typology offered by (Freeman & Perez, 1988), who distinguish four kinds of innovation: (a) incremental innovations (b) radical innovations (c) changes in ‘technology system’ and (d) changes in the techno-economic-paradigm.

**Incremental innovations:** These are changes that occur more or less continuously in a particular industry or service activity, often influenced by a combination of demand pressures, socio-cultural factors, technological opportunities and trajectories. They may occur as a result of deliberate R&D activity or improvements suggested by engineers, users or others involved in the innovation process. While no single innovation has dramatic effects at the system level, the combined effect of a host of incremental innovations can be substantial to the techno-economic systems within which they operate. Examples of an incremental innovation in the automotive industry are ‘Continuously Variable Transmission’ (CVT) and Hybrid Electric Vehicles (HEV).
**Radical innovations:** These may be described as discontinuous events which cannot be described as incremental modifications to existing products or processes. While they are typically distributed unevenly over time and across different sectors, they act as potential springboards for the growth of new markets. While radical innovations can bring fairly dramatic changes to the technological and socio-economic systems their diffusion into society can often be much slower than for incremental innovations.

At this point a further conceptual distinction may be made to the four kinds of innovation of (Freeman & Perez, 1988). Incremental and radical innovations are largely about innovations of particular technologies, whereas technology systems and techno-economic paradigms are discussed at a much higher level of aggregation. The importance of acknowledging different levels of aggregation will be an important construct that will be used again in the discussion of technological transitions and guiding socio-technical change in chapter 4.

**New Technological Systems:** This encompasses far-reaching changes in technology that affect several branches of the economy giving rise to entirely new industrial sectors. In addition to being composed of successful combinations of incremental and radical innovations new technological systems also includes organizational innovations affecting a large number of firms. Together they may form clusters of technically and economically interrelated and mutually interdependent innovations that can facilitate further diffusion of radical innovations into the economy.

**Techno-Economic Paradigms (TEP):** New TEPs represent changes in technological systems that are so far-reaching that their effects can significantly influence entire
economies. The changes involved are so pervasive that they have the potential to transform vast arrays of economic activities such as, drastic reduction in costs, drastic improvements in products, processes and services as well as changes in production, distribution, environmental impacts (both positive and negative) etc. The introduction of sailing ships, water power and mechanization in textiles (1710-1830), steam power and iron (1830-1880), electricity and heavy engineering with steel (1880-1930), automobiles, aircrafts, oil and petrochemicals (1930-1980) are perhaps examples of TEPs from the past (Freeman & Perez, 1988). Given the need for new combinations of incremental and radical technological as well as organizational/institutional changes that may be needed for the realization of a future hydrogen economy, in reference to this typology it may be conceived of a new technological system or techno-economic paradigm. Given the focus on transitions to new socio-technical systems most of the discussion in chapter 4 will be more closely related to these last two forms of innovation.

1.4.5.2 Large Technical Systems

A large body of literature on Large Technical Systems (LTS) has also emerged in the 1980s primarily as a result of the work of (Hughes, 1983, 1987). As the name implies, this literature focused on large technical systems such as electricity networks, telephone networks, railroad networks, internet etc., which stretch vast geographical expanses. From the point of view of this research it is also interesting to note that LTS is not just about technology, but has a socio-technical mode of analysis. As such it introduces the notion of seamless webs (Hughes, 1986) consisting of linkages between heterogeneous elements such as technology, firms, society, contracts, legislation etc., that work together
to form socio-technical configurations. Based on this broader concept of LTS it may be seen as being "socially shaped and society shaping" (Hughes, 1987).

While (Hughes, 1987) distinguishes five phases in the development of the LTS: (a) invention (b) development (c) innovation (d) growth, competition and consolidation (e) momentum, he says little about the decline of LTS, implicitly suggesting that systems last forever after reaching the momentum stage. As we will discuss in a later section, all technological systems are characterized by a time-constant related to their life-span. This decline may be thought of as weakening linkages, between the various elements of the socio-technical configuration, perhaps permitting new ST-systems to emerge. Given the focus on transitions in chapter 4, this limitation of LTS leads us to exploring the more recent literature on transitions theory.

However, before we explore the literature on transitions theory (section 1.4.5.3), we will digress briefly to explore the concept of co-evolution and long-wave theories as they will provide important conceptual aids to inform the discussion on how we may guide socio-technical transitions, in chapter 4.

1.4.5.2.1 Co-evolution in technical and socio-technical systems

If seamless webs represent linkages between heterogeneous elements of socio-technical configurations, then their change over time results in a co-evolutionary process. This co-evolution is between the technical and non-technical elements of the seamless web. In addition to LTS co-evolution is also an important theme within other approaches in Science and Technology Studies (STS), such as in Actor-Network Theory (ANT) and
Social Construction of Technology (SCOT). ANT literature (Callon, Laredo et al., 1992; Latour, 1987) stresses linkages between actors and networks and their influences on each other, while the literature on SCOT (Bijker, 1995; Pinch & Bijker, 1987) emphasizes the importance of multiple social groups in interpreting technology and affecting change in a co-evolutionary manner.

Systems of innovations can be studied from different levels of aggregation such as national systems of innovation, regional systems of innovation, sectoral systems of innovation and technological systems (Geels, Frank W., 2005; Godoe & Nygaard, 2006). While they all have a different focus, a commonality is their emphasis on inter-linkages between system elements and the view that innovation is a co-evolutionary process.

In addition to STS and Innovation studies co-evolution is also an important theme in evolutionary economics, industrial economics and long-wave theories (see next section). The concept of ‘techno-economic-paradigm’ introduced by (Freeman & Perez, 1988) may also be seen as an attempt to indicate how some technologies, production mechanisms and economic structures can interact, re-enforce and co-evolve at particular times.

(Geels, Frank W., 2004) provides a list of different studies which explore different aspects of co-evolution between (a) technology and users (b) technology, industry structure and policy institutions (c) science, technology and the market (d) science and technology (e) technology and culture (f) artefacts, beliefs and evaluation routines, and
(g) technology and society. As such the notion of co-evolution is an unavoidable consequence in complex and inter-linked socio-technical systems that undergo change.

The concept of ‘inertia’ and stability of a system may also be viewed as the gradual strengthening of these inter-linkages over time, permitting certain developments while raising barriers to others. The constrained aspect of this technology co-evolution is also sometimes called path-dependence (Grubler, Nakicenovic et al., 1999). Another interpretation of PD suggests that insignificant events by chance may give one technology the market advantage over another (Arthur, Brian W., 1989).

1.4.5.2.2 Long-wave Theories

Based on an analysis of economic data over a few centuries, some economic historians believe that capitalistic economies show periodic variation (Kondratieff cycles) in prices and economic growth every 50-60 years. The idea that radical innovations were responsible for the growth phases was first introduced by an early 20th century economist Joseph Schumpeter. This theory is highly contested among modern economists, as there is disagreement on the length of these cycles as well as the location of the boom and bust phases, while some disagree altogether of their existence or validity for today’s economies.

It is interesting from the point of view of this research to note that the existence of cycles also emerges from the perspective of co-evolution of technologies. For instance

19 Nicolai Kondratieff was a Russian economist (1892-1938) who first introduced these cycles in his book “The Major Economic Cycles” (1925) after analyzing economic data over the 19th century.
(Rosenberg, 1982) argued that the growing productivity of industrial economies were largely a result of "the complex outcome of large numbers of inter-locking and mutually re-enforcing technologies", and suggested the importance of considering the major clustering of innovations from a systems perspective. The idea of cross-sectoral clustering between technologies was further developed by (Ayres, 1989) who argued that the large scale production of the automobile was possible due to developments and technological inter-dependencies in steel, internal combustion engine, gasoline etc. Furthermore, analyzing technological developments over the past 200 years (Grubler, Nakicenovic et al., 1999; Nakicenovic, Nebojsa, 1991) point to 3 rather clear clusters of technologies: the first saturated around 1865 (canals, water power, sails, iron-casting, turn-pikes), the second around 1930 (railways, steam-ships, telegraph, heavy duty industry), and the third is apparently saturating now (electric power, oil, cars, radio, TV, petrochemicals). These bear some resemblance to the four successions of TEPs (Freeman & Perez, 1988) mentioned earlier.

These ideas about saturating clusters of technologies and their co-evolution, will also serve as an important building blocks as we explore technological transitions in the context of socio-technical change in chapter 4.

1.4.5.3 Transitions Theory

The literature on innovation and STS contributes significantly to our understanding of combined social and technical systems and their stability, once they have emerged. The literature also highlights the significance of co-evolution between technologies and between technology and society. Also historical analyses show us that there are certain
techno-economic patterns evident from our past. However, not much has been said about how systems change or about transitions from an old to a new (Geels, Frank W., 2005; Malerba, 2002).

Transitions have been defined by (Rotmans, Jan, Kemp et al., 2001) as transformation processes in which society (or complex sub-systems of it) changes in a fundamental way over a generation or more. They also suggest that although the concept of transition can be viewed from different aggregation levels (companies, sectors, countries and regions) in terms of social organization, roughly three different levels may be distinguished: micro, meso and macro. These levels fit closely with the classifications used by (Rip & Kemp, 1998) to describe changes in socio-technical systems, namely the division into technological niches, technological regimes and socio-technical landscapes (ST-landscapes). Such a multi-level perspective (MLP) was originally developed to understand regime shifts (Kemp, 1994; Kemp, Schot et al., 1998; Rip & Kemp, 1998; Schot, Hoogma et al., 1994). The MLP was further refined and developed by (Geels, Frank W., 2002, 2004, 2005).

1.4.5.3.1 The Multi-Level Perspective

Although the concept of technological regime (meso level) was first introduced by (Nelson & Winter, 1982) its definition was restricted to engineers, their cognitive routines and the technical trajectories that result from their activities. (Rip & Kemp, 1998) however recognizing its social context defined technological regimes more broadly as, “A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills
and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures". (p. 340)

The rules of the regime bring it stability as they act as barriers to actions not consistent with it. However stability is not automatic as rules may need to be reproduced and re-affirmed in order to maintain their status. An interesting analogy is made by (Geels, Frank W., 2005) between regime rules and neural networks in the brain: "Connections in neural networks grow stronger or weaker as they are used more or less frequently. Connections may even die out if not used at all. Likewise, rules change as they are used. Rules that are no longer used gradually die out". As such, rules may be modified and re-interpreted as a result of the multiple interactions between the actors of the regime. It should be noted that (Geels, Frank W., 2002, 2005) further expanded the concept of technological regime to socio-technical regimes (ST-regimes) to more explicitly include the rules and activities of the other social groups other than simply engineering communities. He adds further texture to the concept of ST-regimes by clarifying its various dimensions as shown in Figure 1-4.
The ST-regime exists within the context of the *socio-technical landscape* (macro level). (Rip & Kemp, 1998) used the metaphor of the landscape to introduce the concept of socio-technical landscape (ST-landscape) in order to represent the ‘hardness’ or the material context (the built environment) of society. The concept of ST-landscape also contains a number of heterogeneous aspects such as social values, policy beliefs, worldviews, political coalitions, prices and costs, trade patterns, incomes, wars and environmental problems. From an analytical standpoint landscapes may be thought of as forming gradients for action. This means that landscapes make it easier for socio-technical developments to move in particular directions over others. Figure 1-5 below helps to visualize the concept of gradients in the ST-landscape.
According to (Geels, Frank W., 2005) there are two types of changes in landscapes. The first refers to relatively rapid changes as a result of external shocks from wars, oil price, economic recession etc. The second is more gradual and results from changes in demography, culture or political ideologies.

Finally the Niche (micro level) is a protected space where novelties may be developed and learning may occur with the expectation of future applications. It is reasonable to expect radical innovations to need such protection as they may be viewed as ‘hopeful monstrosities’ (Mokyr, 1991). The notion of a niche may be differentiated into technological niche and market niche (Geels, Frank W., 2004). Although a niche technology could be operating in either of these niches, in the case of the former it may be sustained by subsidies and strategic investments while in the latter it may be sustained.
by regular markets (although small) on their own or in combination with subsidies and strategic investments. Also in the former, design rules and users are often not properly defined or articulated and thus are more unstable than the latter. Here after, unless otherwise specified, the term niche refers to both types.

The significance of the niche in the multi-level perspective is that it serves as the seed for regime change (Kemp, Schot et al., 1998). Whenever there is instability or tensions within the ST-regime due to its own internal dynamics or due to pressures from the landscape level, radical innovations in the niche level can take advantage of these tensions and break into regular markets. Figure 1-6 below graphically illustrates how new technologies may emerge as a result of the dynamics between the three levels of the MLP. When novelties emerge they emerge within the context of the rules of the regime and its specific problems. The solid arrow represents more direct influence from the regime while the dotted arrow represents a much weaker and less direct influence from the ST-landscape.
The rules of the niche in general are not as well defined as the rules of the ST-regime. At the niche level it is still unclear who the users are, what their wishes are, the user practices, how much they are willing to pay etc. Technologies in the niche are not held together by a stable network, but by dedicated efforts of a small network of actors who are believers in the product and its future potential (Geels, Frank W., 2005). Niches also provide a space for building these social networks (between producers, suppliers etc) that would take on increasing responsibility if they succeed in emerging into regular markets. Learning is also critical for niches if they are to be successful in the future. Learning effects as well as other niche dynamics discussed above have been studied extensively under the field of Strategic Niche Management (SNM) (Hoogma, Kemp et al., 2002; Kemp, Schot et al., 1998; Schot, Hoogma et al., 1994), which we will turn to next.
1.4.5.3.2 Strategic Niche Management

SNM has been defined by (Kemp, Schot et al., 1998) as "The creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology." (p186)

Scholars of SNM suggest 3 processes that are important for the development of the niche: (a) formation of the social network to support the novelty (b) learning processes to improve the price/performance ratio of the technology as well as alignment or contextualization of the technology with the broader socio-technical systems, and (c) the articulation and adjustment of expectations and visions.

These 3 processes may be examined from the context of Canada's Hydrogen Highway project (Ch2). First, the Hydrogen Highway Steering Team brought together various actors interested in the realization of a future hydrogen based economy (industry, local/provincial/federal government representatives) within the province of British Columbia and formed coalitions and networks in order to work toward a common goal (network formation). Secondly, the planned demonstration projects for the 2010 Olympics provide many opportunities for learning. SNM scholars make a distinction between 1st and 2nd order learning, where the former refers to learning about the technology itself (most common) and the latter refers to the exploration of the norms and values of the users and their mindset (Hoogma, Kemp et al., 2002). Finally the
demonstrations and experimentation conducted by the actors, help shape their expectations and visions and may contribute to making it more robust. As more relevant actors enter the network these visions can become more robust and expectations may become more stabilized. It should be stressed that exploring the relevance of SNM to analyze Canada’s Hydrogen Highway is not an objective of chapter 4 or this dissertation. The purpose of the above discussion was for contextualizing some of the ideas from the SNM literature. The application of SNM for the analysis of Canada’s Hydrogen Highway has been done elsewhere by (van der Vossen, 2005), who suggested that it may be used for learning and for supporting the development of this technological niche.

1.4.5.3.3 Transition Management

SNM may be viewed as part of a broader approach to managing transitions – transitions management (TM) – where the focus is on a transformation of the entire society or socio-technical system. The concept of the multi-level perspective and its different socio-technical levels naturally would lead one to think about the possibility of managing transitions. The literature on TM has emerged from the Netherlands (Hoogma, Kemp et al., 2002; Kemp, Rip et al., 2001; Kemp & Rotmans, 2004; Kemp, Schot et al., 1998; Rotmans, Jan, Kemp et al., 2001) and its utility demonstrated through its application on the Dutch energy and transport sectors.

TM has been described by (Kemp & Rotmans, 2004) as “...an integrative and multi-scale framework for policy deliberation, choice of instruments and actions by individuals, private and public organizations and NGOs. It aims for long-term change through small steps informed by transition goals and sustainability visions. It is not an instrument but a
Other key elements of the TM are long-term thinking, a special learning philosophy (learning-by-doing and doing-by-learning) and learning about a variety of options, an orientation towards system innovation and thinking in terms of multiple dimensions, multiple actors and multiple levels (Kemp & Rotmans, 2004; Rotmans, Jan, Kemp et al., 2001). While TM stresses that no single actor can steer a transition and that it has to be a collective process, it does emphasize the guidance from actors within the niche.

A major criticism of TM is the emphasis of the bottom-up approach of the niche based model. Critics (Berkhout, Frans, Smith et al., 2004) have argued that in addition to bottom-up approach (niche-regime), transitions may also occur due to influences from the landscape downward on the ST-regime in a top-down fashion. They argue that while the social movement for Alternative Technologies sought a process of change more consistent with the niche-based model, the wider environmental movement sought more directly to influence changes at the higher ST-landscape level (and regime level) of institutions and economic structures. This notion of the possibility of socio-technical transitions from both directions will be an important building block for chapter 4.

1.4.5.3.4 Transition Contexts

While being critical of the bottom-up niche model (Berkhout, Frans, Smith et al., 2004) argue for a more differentiated notion of transition by proposing a framework that consists of 4 different transition contexts. The 4 contexts may be conceptualized as

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20 It is interesting to note the importance of society, their goals and visions as an important goal for transition management. We will return to the significance of guiding visions to the research in this dissertation (Ch4 in particular) in section 1.4.5.4 below.
existing in one of 4 quadrants (see Figure 1-7) created by two axes: co-ordination (high/low) and resources (internal/external).

Figure 1-7: Transition Contexts of Berkhout et al.
Source: (Berkhout, Frans, Smith et al., 2004)

The degree of co-ordination on the x-axis refers to that of regime actors and the y-axis refers to whether the resources available to the regime actors (to respond to selection pressures) are available from within the regime or external to it. The four transitions that emerge from this model are labeled ‘purposive transitions’ (deliberate change caused by actors outside the regime), ‘endogenous renewal’ (deliberate change fostered by regime members), ‘re-orientation of trajectories’ (spontaneous change resulting from relationships and dynamics within a regime) and ‘emergent transformations’ (the unintended consequence of changes wrought outside prevailing regimes).
Berkhout et al.'s differentiated transition contexts add more texture to our understanding of transitions as it emphasizes the importance of recognizing that transitions are essentially a result of a mixture of intended and unintended outcomes of historical processes. In addition, regardless of the degree of co-ordination (and the pressures from the niche or landscape levels) according to Berkhout et al. the 'adaptive capacity' of the regime may be crucial to the type of transition that may occur. We will return to how these contexts relate to the envisioned transition to a hydrogen economy in Ch4.

1.4.5.4 Guiding ST-change - Visions and Technological Expectations

Visions and expectations of the future are an important part of future studies and hence of socio-technical change. While traditional forecasting studies do not rely on visions or expectations, they are the essence of backcasting studies. Backcasting is an approach which works backwards from future scenarios defined in terms of their desirability (Robinson, John B., 1982; Robinson, J.B., 1988; Robinson, John B., 1990). An elegant analogy contrasting backcasting and forecasting approaches is found in (Robinson, John B., 1996): "Forecasting is driving down the freeway and, from one's speed and direction, working out where one will be by nightfall. Backcasting is deciding first where one wants to sleep that night and then planning a day's drive that will get one there."

In relation to the discussion on socio-technical transitions, forecasting approaches, which simply try to predict the future, are somewhat less interesting. They are not designed for problem solving or for supporting transitions to a future where human choices have any input. The idea behind studying transitions and transitions theory is to understand if and how we may solve some of the problems of the current ST-regime and move towards a
more desirable and perhaps sustainable ST-system. As such the explicitly normative nature of backcasting approaches (Robinson, John B, 1990) and their guiding visions fit well with the study of ST-transitions. This is why, as discussed earlier they form an important component of the Transition Management approach (Kemp & Rotmans, 2004).

In the context of governance of sustainable ST-transitions (Smith, Stirling et al., 2005) also discuss the importance of visions and expectations of the future as being a prerequisite for having the power to affect change. However, they point out that the process of constructing a coherent vision of the future is far from unproblematic and that problem framing, co-ordination of responses and agreeing on how to use available resources are not straightforward. Different actors may share different perspectives and visions of the future, therefore a participatory process involving a diverse set of stakeholders for exploring alternative futures is one way to recognize the different perspectives, engage in a debate and facilitate learning. (Robinson, J.B., 2003) suggests how through the process of engaging with stakeholders the desired future becomes an emergent property of the process (second generation of backcasting) of “structured conversations about future options, consequences and tradeoffs, that combine expert understanding with the knowledge, values, and preferences of citizens and stakeholders”. Therefore, rather than the ‘desired future’ being determined in advance (as it often is when individuals or groups (lay and expert) with similar interests and views align themselves with each other) it becomes the product of a social learning process, between experts and ordinary citizens.

However visions and expectations expressed of desirable futures are rarely a result of such processes social learning exercises, with balanced participation. Instead, they
emerge more commonly as "... 'bids' that are deployed by actors in processes of 
coalition-formation and coordination" (Berkhout, Frans, 2006). These bids also tend to 
be bids for particular technologies or technological configurations, implying futures that 
are technology-driven. This may be a result of an implicit bias toward the 'technology' 
component of a socio-technical system and the importance given to its apriori selection in 
guiding socio-technical change. The extent to which future studies and discussions on 
socio-technical change are 'technology-driven' and the implications of that, will serve as 
an important building block and point of discussion for Ch4.

1.4.5.4.1 Hydrogen Futures

Section 1.4.3 was focused primarily on the technological aspects of hydrogen energy 
systems. This section will complement that by providing a review of the hydrogen futures 
but will do so within the context of the role of guiding visions and expectations in 
shaping it.

The notion of a hydrogen future powered by hydrogen’s energetic properties was first 
envisioned by Captain Harding - an engineer in Jules Verne’s science-fiction novel from 
1874, The Mysterious Island (Verne, 1959) - "Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable. Some day the coal-rooms of steamers and the tenders of locomotives will, instead of coal, be stored with these two condensed gases, which will burn in the furnaces with enormous calorific power."
Over a century later, motivated by the high petroleum prices, real life engineers and scientists predicted or forecasted that a hydrogen economy was inevitable and that it would become a reality by the 1990’s (Bockris, 1977). Clearly neither prediction has yet come to pass. While much of the interest in hydrogen in the seventies (post oil crisis) subsided due to the rapid improvements in energy efficiencies and energy conservation of the 1980s, the 1990s saw another wave of interest in fuel cell and hydrogen energy systems and associated hydrogen futures.

Figure 1-2 and 1-3 showed the various pathways and configurations that exist for designing future hydrogen energy systems. However, the figures don’t have a temporal component to them. In other words, one could conceive of one configuration (i.e. fossil based) making a transition over time into another (i.e. non-fossil based). Thus it is important to recognize the additional heterogeneity that exists when the temporal component is considered.

On route to a renewable energy based hydrogen future (Rothstein, J., 1995a; Rothstein, J., 1995b) argues for a nuclear and fossil energy based hydrogen economy to precede it while (Bockris, 2007) also speaks in favour of a future hydrogen energy system based on renewable energy, but is vehemently opposed to the transition to it via a nuclear or fossil energy route. (Muradov & Veziroglu, 2005) also suggest a renewable energy based hydrogen economy in the distant future, but in their scenario of a hydrogen-carbon economy they speak of a “transition from the current hydrocarbon-based economy to a

\[21\] This is based on the Catalytic Decomposition of Natural Gas (CDNG), which produces H2 and solid carbon, with no CO2 emissions.
hydrogen–carbon economy as a half-way point to the ultimate hydrogen-from-renewables economy of the future". The use of carbon capture and storage (CCS) technologies for reducing CO2 emissions, is also recommended for intermediate hydrogen futures that are fossil intensive (Blok, Williams et al., 1997; Simbeck, 2004). This illustrates the point that not only is there heterogeneity in the end points for a hydrogen future but also in the transitions and intermediate hydrogen futures en route to any particular end-point.

Others yet take a sector based perspective to guiding the evolution of hydrogen futures. For instance (Penner, 2006) warns against committing too early to a large scale hydrogen infrastructure (regardless of hydrogen source) and hydrogen based fuel cell vehicles and suggests the introduction of hydrogen fuel cells in the stationary power sector. The argument made is that with the experience gained from hydrogen and fuel cells in the stationary power sector, a re-examination of the transportation sector in the future would lead to a clearer picture of how to proceed. Others, based on highly technical analyses, suggest that stationary power for buildings and mobile power in cars can be integrated to develop more efficient systems such as the fuel cell powered hypercar\textsuperscript{22} (Lovins, A. B., 1999, 2002) and that deployment of fuel cells in light-duty transport can be sped up through such efficient integration.

(Farrell, A. E., Keith et al., 2003) take a modal approach to guiding a transition to a hydrogen future. Their analysis based on cost-optimization leads them to recommend that

\textsuperscript{22} Lovins' hypercars will be built from ultra-light carbon-fibre composite material which is expected to be stronger, lighter and have low drag and get the equivalent of 99 mpg.
heavy-duty modes (freight transport, marine etc) would be a less costly way of introducing hydrogen into the transportation sector, and a more effective way of advancing hydrogen-related technologies more widely in light-duty vehicles. As such they recommend heavy duty freight as a potential strategic niche where learning can occur and its management (SNM) leading to a transition toward a hydrogen future.

As mentioned in section 1.4.3, two system configurations or architectures exist for hydrogen transport: centralized and decentralized architectures. (Ogden, 1999b) describes 5 different variants of these two architectures (see Figure 1-8 below). The first three are based on centralized architectures and the last two are decentralized hydrogen production and delivery mechanisms. While for a mature hydrogen economy (i.e. large demand for hydrogen from fuel cell vehicles) the large infrastructure costs associated with a centralized architecture may be justifiable, the flip side of that statement is that it is hard to expect a large demand for hydrogen from FCVs to develop without an infrastructure to support it. This is sometimes referred to as the “chicken and egg problem”. One way to get around this problem according to (Ogden, 1999b) is to produce hydrogen where it is needed and when it is needed. The Pembina study (Pembina, 2000) is also more supportive of a decentralized system, since its size can be expanded incrementally as the demand for hydrogen increases. Alternatively, a decentralized architecture may serve as a transitional phase to a centralized infrastructure if that is deemed more appropriate.
Others do not see a "chicken and egg problem" and support a decentralized architecture simply because they believe it is more efficient and cost-effective than centralized architectures (Lovins, A. B., 2003). Other reasons given in support of decentralized
system are, the reduced vulnerability to security risks and the ability to take advantage of the already existing natural gas grids (for hydrogen production from SMR) (Barreto, Makihira et al., 2002). Others favouring the distributed generation (DG) model for electricity production or the distributed nature of the internet also find it easier to support the decentralized architecture for hydrogen production (Clark, Rifkin et al., 2005).

The hydrogen futures literature also includes visions which are based less on any systematic analysis and more on a romantic association with the notion of a hydrogen economy. For instance (Cruver, 1989) describes hydrogen as “the ultimate economical energy for mankind”. While describing some of the environmental problems of today, they paint hydrogen as the ultimate solution to all our problems. (Cruver, 1989) focuses on all of hydrogen’s advantages based on its physical and chemical properties, without discussing any of the challenges for hydrogen as an energy carrier or the challenges for fuel cells, as discussed in some of the more balanced analyses of hydrogen futures (Conte, Iacobazzi et al., 2001; National Research Council USA, 2004). Cruver also makes reference to others who believe in hydrogen replacing fossil fuels, just as electricity replaced oil for lighting, diesel replacing steam engines or the jet airplane replacing the piston-engine aircraft. Given the complexity of the socio-technical landscapes, regimes and niches discussed earlier and it’s embedded cultural beliefs, value systems, policies, rules, etc, it may be too simplistic to point to selective technologies and fuels that emerged from niches (due to a variety of conditions), without analyzing how and why they were successful, while countless others did not. Similar visions of the
inevitability of a transition to a hydrogen economy are also expressed by (Dunn, 2001; Rifkin, 2002)

Scenarios are also used as a tool to probe hydrogen futures. (Barreto, Makihira et al., 2002) develop a global hydrogen-economy scenario (labelled B1-H2) based on the SRES B1 scenario (Nakicenovic, N, Alcamo et al., 2000). This detailed scenario analysis based on a qualitative storyline and quantitative modeling show that “In an affluent, low-population-growth, equity and sustainability-oriented B1-H2 world, hydrogen technologies experience substantial but plausible performance and costs improvements and are able to diffuse extensively”. The scenario also assumes a major shift in hydrogen production from fossils to renewable energy in the long-term and that fuel cells and other hydrogen technologies play a major role in the transformation of the global energy system to a more flexible, less vulnerable, distributed energy system with substantial improvements in energy intensity, energy security and decarbonization with relatively low climate impacts. However, the authors acknowledge that a transition to such a future would require overcoming a number of technological, institutional, political and social hurdles as well as substantial international efforts to develop of collaborations and partnerships across public and private sectors.

Other national and sub-national level scenario analyses are also used to guide more near-term efforts of realizing a hydrogen economy. As discussed earlier (Fukuda, K., 2004; Fukuda, K., Kobayashi et al., 2001) has developed a scenario for the introduction of fuel cells in Japan, which is a highly technical analysis; (Sorensen, Hauge Petersen et al.,
2004) describes two hydrogen energy scenarios for Denmark based on renewable energy but differing on their degree of decentralization; and (Ogden, 1999a) examines the technical and economic feasibility of a hydrogen refueling infrastructure for fuel cells vehicles and discusses possible scenarios for introducing hydrogen as a fuel for fuel cell vehicles in Southern California.

The discussion above provides some of the main currents and contested view-points in the hydrogen futures literature. There seemed to be a variety of levels and scales at which hydrogen futures were probed. Some were based on a sectoral level analysis, some on different transport modes, some emphasized the different system architectures, and others focused on the international, national or sub-national scales. Also it was evident that there were differences in the tools used in probing hydrogen futures, such as scenario analysis tools, purely technical analyses, normative visions or forecasts. Finally, any given study could be composed of some combination of a tool for probing the future and a particular level/scale of analysis. This adds more heterogeneity to the hydrogen futures literature than simply the heterogeneous pathways of Figure 1-2 and 1-3 or the sequence/progression in which they may follow a transition path towards a possible renewable energy based hydrogen future.

Based on a review of 40 studies published between 1996-2004 (McDowall & Eames, 2006a) confirm the highly contested nature of the hydrogen futures literature, with regards to the different sources for hydrogen, system architectures and the roles of nuclear power and carbon sequestration. Also, they introduce a typology that helps
organize the heterogeneous literature noted above. The typology consists of six broadly
distinct (but overlapping) types of studies identified as: (1) Forecasts; (2) Exploratory
Scenarios; (3) Technical Scenarios; (4) Visions; (5) Backcasts/Pathways; and, (6)
Roadmaps. The first three are further grouped as being ‘descriptive’ while the last 3 are
considered ‘normative’ in nature. While the individual studies themselves did not
necessarily classify their work as such, this first attempt to organize this growing and
heterogeneous literature may prove to be useful for those trying to attain a holistic view
of it.

Building on the idea that the ‘interpretive flexibility’ of a technological guiding vision is
key to its rhetorical power (Berkhout, Frans, 2006), in reference to the hydrogen
economy (Eames, M., McDowall et al., 2006) argue that its rhetorical power and
promotion by a broad range of interest groups, is a result of its great ‘interpretive
flexibility’. However, one may argue that such interpretive flexibility may not be unique
to hydrogen futures. Similar interpretive flexibility is also possible for other types of
energy futures. For instance, *hydrocarbon futures* may derive its interpretive flexibility
from the various hydro-carbon and hydrocarbon-based technologies that are pre-
commercial or existing in protected technological or market niches; i.e. clean-coal
technologies, synthetic crude-oil and synfuels (Brandt & Farrell, 2007), coal and carbon-
sequestration , energy from coal-bed methane, methane-hydrates, energy multi-plexes,
poly-generation of energy carriers and chemicals (Jaccard, M., 2003), Fischer-Tropsch
liquid hydrocarbons (Steynberg & Nel, 2004), etc. As such a variety of futures exists
within hydrocarbon based fuels and related technologies that may lead to great
interpretive flexibility. A similar argument can also be made for renewable energy and related technologies. Therefore, such interpretive flexibility would give each of those guiding visions (hydrocarbon vision, or renewable energy vision) at least the same level of rhetorical power as for the hydrogen economy.

It does seem however that these guiding visions of socio-technical change seem heavily reliant on particular technologies, technology combinations or technology-fuel combinations, and on expectations regarding their viability of transition and sustainability. Hence the guidance for our future seems to be *technologically driven*. As noted earlier, we will return to this seemingly inescapable choice about technologies and its usefulness or lack thereof, for thinking about and guiding future socio-technical change, in chapter 4.

1.4.5.5 Diffusion of Technologies and the Logistic Curve

Appendix E provides a brief review of the logistic curve (also called S-curve) and its usefulness in describing the diffusion of technologies. It also discusses the bell-curve and the 5 different adopter categories that define the diffusion of technologies within our social system. While these constructs are not critical to the main discussion within this dissertation, for the sake of completeness they have been included in Appendix E.

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23 The point made here recognizes that hydrogen, hydrocarbon and renewable energy futures are not necessarily mutually exclusive of each other. For instance, in theory hydrocarbon technologies and futures may not need hydrogen or renewable energy; similarly renewable energy futures may need little or no hydrocarbons or hydrogen; however, since hydrogen is a secondary energy carrier, hydrogen futures need to include primary energy sources such as hydrocarbons or renewable energy or both. Given this potential connection between these somewhat overlapping but distinct futures, depending on the rates and direction of socio-technical change in any particular region, elements of one could be incorporated into the other.
In the interest of completeness it should also be pointed out that another sub-literature within the diffusion literature discusses technology diffusion at the level of individual users and their decision-making process (Dosi, 1991; Geroski, 2000; Stoneman, 2002). While a number of theoretical modeling frameworks exist based on a variety of different assumptions about adopters, their mental models and how they make decisions, since none of the research within this dissertation operates at the level of an individual or individual decision-making, this literature will not be discussed in this chapter.

1.4.6 H2 Futures, Sustainability Assessment & Technical Change

Before closing the literature review of the three spheres identified in Figure 1-1, it is worth noting some recent work occurring at the interface of hydrogen futures, sustainability assessment and socio-technical change. While to our knowledge little work has been done at this intersection, it is important to compare and situate this dissertation with some exceptions in this area.

Partial exceptions in this area are (Hisschemoller, Bode et al., 2006) who from the perspective of political theory explore the relationship between technologies and institutions based on different paradigms of governance and their possible bias with respect to a hydrogen future. As far as the intersection of the three spheres in Figure 1-1 is concerned however, their work while analyzing the role of institutions in socio-technical change (i.e. toward a hydrogen future) does not touch on the assessment of sustainability. This is not a weakness or criticism, but simply an observation of its research intersections.
(Shackley, Simon & Green, 2007) makes use of the literature on socio-technical transitions to analyze the past, current and future change in the UK's energy system exploring the different transition pathways to a decarbonized future. One of the transition pathways (re-configuration pathway) briefly discusses the possibility and challenges for making a transition to a hydrogen future in the UK. However, this discussion, while acknowledging the heterogeneity on the supply and demand side, occurs at a very high-level – hydrogen economy. Also, the assessment of sustainability of energy systems or hydrogen systems was not part of its focus. Nevertheless both of the above works while focusing on different levels of aggregation and dimensions of analysis, touch on important aspects of the three spheres of Figure 1-1.

On the other hand some of the recent work from the UK Sustainable Hydrogen Energy Consortium (UKSHEC) seems to be situated at one of the interfaces between these three areas. However, to use the analogy of 'different dimensions' of the ST-regime or 'levels' within the MLP, each circle may also be conceived of not as existing in two-dimensions (as shown in Figure 1-1) but as having different levels of aggregation or composed of different dimensions or even being applied to different situations. For instance to take the research area of Hydrogen Systems and Futures, one may focus on the details of the particular hydrogen and fuel cell technologies in specific applications (transportation, hydrogen storage, fuel cell diagnostic systems, others may focus and the integration of these systems into a functioning whole. It is also possible to focus on the generation of scenarios that emerge from the heterogeneous pathways of hydrogen
energy systems (Figure 1-2 and 1-3) and yet others may be interested in developing visions of hydrogen futures through stakeholder engagement. Even the stakeholder engagement may be conducted with experts only, lay citizens only or both.

The point is that these are all important components (although at different levels and dimensions) of the bigger picture of hydrogen futures, which no one group can address alone. The same holds true for the other research areas as well. As such there is no unique interface between any three research areas and it is harder to make the argument that any one level, dimension or combination of them is more significant than the next. They all contribute differently and in important ways to the overall discussion and understanding.

Given the seemingly common research interface between this dissertation and the recent work of the UKSHEC, in the next section we will take a closer look at it to explore the commonalities, differences and how they relate to each other in general.

**H2 Visions, Sustainability Appraisal and Transitions of UKSHEC Scenarios**

Six visions\(^\text{24}\) of a hydrogen future for the UK were developed by the UK Sustainable Hydrogen Energy Consortium (UKSHEC) which were then subjected to an appraisal using a method called ‘multi-criteria mapping’ (MCM\(^\text{25}\)). This was done within a participatory process involving 15 expert stakeholders, in order to explore the various sustainability dimensions of the six visions (McDowall & Eames, 2006b). The visions

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\(^\text{24}\) The 6 visions are: 1. Central Pipeline, 2. Forecourt Reforming, 3. Liquid Hydrogen, 4. Synthetic Liquid Fuels, 5. Ubiquitous Hydrogen, 6. Electricity Store. Visions 1-4 assume hydrogen only in the transport sector while visions 5 and 6 assume hydrogen as a transport fuel as well as providing other energy services. In terms of system architecture visions 1 and 6 are based on decentralized architectures, visions 2, 3 and 4 are centralized architectures while vision 5 includes both.

\(^\text{25}\) According to the authors an adapted MCM was used in their sustainability appraisal.
were developed through a review of the hydrogen futures literature and an earlier visioning workshop involving 40 UK hydrogen stakeholders (McDowall & Eames, 2004). These workshops were part of a multi-year multi-million dollar initiative of the UKSHEC. According to (McDowall & Eames, 2006b) this work is "part of a backcasting scenario project, which aims to develop visions of a sustainable hydrogen future [for the UK], and then explore the pathways by which those visions might be achieved". The elements of the broader socio-economic project of UKSHEC are shown below in Figure 1-9.

![Figure 1-9: UKSHEC Scenarios Project](image)

**Figure 1-9: UKSHEC Scenarios Project**  
Source (McDowall & Eames, 2006b)

The broader UKSHEC scenarios project outlined in Figure 1-9 has some interesting similarities and differences to the research contained within this dissertation. First, they both have a connection to hydrogen energy systems and futures. While the former is driven by the question of how the UK might move to a sustainable hydrogen energy system (through the 6 hydrogen visions for UK), the research contained within this
dissertation does not assume hydrogen energy future as an end-state but merely as a medium through which the broader concept of socio-technical change and transitions may be discussed. As we will see in chapter 4, the discussion on ST-transitions is driven from the point of view of the kind of future world we might want to live in, the answer to which leads to a particular form of technological system (hydrogen or otherwise), rather than the reverse which may be described as being a *technologically-driven* approach to making choices about the future.

As argued in chapter 4, the historical record of our transitions is more in line with the second approach described above as we seem to be obsessed with making choices between technologies. Our tradition is also somewhat consistent with the bottom-up approach of technological change (niche-to-regime) (Geels, Frank W., 2002), which I also argue that it ignores top-down approaches to socio-technical change. Elsewhere (Berkhout, Frans, Smith et al., 2004) has also been critical of the bottom-up approach to transitions.

On the topic of hydrogen futures and sustainability appraisal there are also some important differences. First, it should be noted that if we continue with the tradition of choosing between technologies and technological systems, then we need improved methods for assessing sustainability between different technological options. The UKSHEC project conducted an appraisal of different visions of the future (McDowall & Eames, 2006b) by interviewing 15 experts on their ratings of the six UK hydrogen visions, based on criteria defined independently by each expert. As such the appraisals
are based on elicitation of expert judgment on different aspects of the hydrogen visions. The adapted MCM tool used by (McDowall & Eames, 2006b) bears closest resemblance to the MCA process discussed in Chapter 3. Also the participatory backasting aspect of their appraisal may be considered as being part of the family of Stakeholder Analysis Tools, according to the SustainabilityA-Test (de Ridder, 2005). As such the adapted MCM and the participatory backasting tools selected were implicitly deemed most appropriate, from the universe of tools, for the sustainability appraisal of UK hydrogen futures.

In contrast, chapter 3 is based on the premise that since the results of the assessment may depend strongly on the tools used, for a sustainability assessment, tool selection needs to be an explicit and systematic process rather than based on factors such as availability or convenience. Therefore, based on that premise and on a review of a wide selection of assessment tools in the literature, a framework (sustainability assessment framework) is proposed in chapter 3 that would aid in the tool selection process. While the sustainability appraisal of the UKSHEC project may be described as being a qualitative appraisal of the UK hydrogen futures (i.e. expert judgment of hydrogen visions), the nature of the problem being assessed (described below) in Chapter 3 required more attention to analytical tools and their selection. Put another way the UKSHEC project appears to take a more social science approach to sustainability appraisal, while Chapter 3 in this dissertation tries to balance the contributions from both, the hard and soft sciences, in exploring the methodology of sustainability assessments.
In Chapter 3 the scope of the object being assessed was not a set of visions for hydrogen (as in the UKSHEC project) but a variety of light-duty vehicle technologies and fuels – including fuel cell and internal combustion engine technologies in combination with fuels derived from a variety of primary energy sources (Figure 3-3 in chapter 3). Expert judgment is a recommendation that emerges from the integrated assessment in chapter-3, for components of the problem with large uncertainties and knowledge gaps. However, it is not the sole method for assessment. This result is also consistent with other recommendations from integrated assessments that see expert judgment as being an important part of the overall assessment process (Morgan, G. & Dowlatabadi, 1996).

It should be noted that as recommended in Ch3, Sustainability Assessment must include broad participation from different stakeholders and the public. The visioning and sustainability appraisal of the UKSHEC included 15 expert stakeholders but this should be extended to the broader public in the UK. Similarly as noted in Chapter 3, and in the section on future research in Chapter 5 (Conclusions), a complete sustainability assessment would be conducted within a broad participatory process. Hence, in their future work both studies could include wider participation, beyond expert analysis.

Another noteworthy working paper, by the same authors, was based on theoretically informed transition paths to the UK hydrogen scenarios (Eames, Malcolm & McDowall, 2006). Here the authors map four of the six UK hydrogen visions onto Berkhout et al.’s four quadrants of transition contexts (see Figure 1-7) (Berkhout, Frans, Smith et al.,
They also relate the four visions (and the four quadrants) to four archetypal governance paradigms described by (Hisschemoller, Bode et al., 2006).

As before, the discussion is fixed on different hydrogen end-states to the exclusion of other possible sustainable energy systems. It raises the question if the goal of the UK vision is framed as being a ‘sustainable energy system’ or if it is constrained to finding a sustainable energy future within the realms of hydrogen futures. The transition pathways explored in (Eames, Malcolm & McDowall, 2006) seem to suggest the latter. As alluded to above, the focus in this dissertation (particularly in Chapter 4) is not about transitions to a particular energy future (hydrogen, renewable, nuclear etc) which is described as a *technology-driven approach* (bottom-up transition dynamics); but as the title of this dissertation suggests (‘Beyond Energy Futures’) it goes beyond making choices about energy technologies and energy futures and suggests to the reader that it is possible to think about socio-technical transitions depending on the kind of future we want to live in and its broader characteristics. Decisions and choices made at that level are at the level of the values, deep rooted beliefs etc., of the landscape, which may influence the regime and niche in a top-down manner (top-down transition dynamics).

(Berkhout, Frans , Smith et al., 2004) have also been critical of bottom-up niche to regime type transition dynamics often seen in the transition management literature, for being too reliant on solutions grown in niches. Arguably, the transitions pathways to the UK hydrogen visions (Eames, Malcolm & McDowall, 2006) also rely on the niche for the transitions and as such would be subject to the same critique.

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26 The four governance paradigms are: i) Governance by government, ii) Governance by policy networking, iii) Governance by corporate business, iv) Governance by challenge.
It needs to be emphasized that the point being made here is that while there are some similarities between areas of this dissertation and that of the UKSHEC project there are some important differences in scope, methods and research focus. Nevertheless, they both are boldly traversing relatively uncharted multidisciplinary realms, and in so doing are opening up new areas of future research and contributing toward the research agenda of Sustainability Science (Kates, Clark et al., 2001) as well as toward the research on socio-technical change and transitions.
1.5 Thesis Structure

Chapter 1
- Chapter Introductions
- Literature Review

Chapter 2
- Case-study (Hydrogen H’Way)
- Preliminary Sustainability Assmt.

Chapter 3
- Sustainability Assmt. Framework
- Application on Transportation Example (including Hydrogen Fuel Cell Vehicles)

Chapter 4
- Bridging the gap: Technical Change to Socio-Technical Transitions
- An approach for Future Transitions

Chapter 5
- Significance of Research
- Overall Conclusions
- Comments on Future Research

Figure 1-10: Schematic Representation of Thesis Structure
1.6 References


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2 Characterization and Sustainability Assessment of Canada's Hydrogen Highway

2.1 Introduction

The seeds of a possible future hydrogen based economy or energy system, were sown in the 18th & 19th century with the discovery of hydrogen by Henry Cavendish in 1766 and the discovery of the fuel cell by William Grove in 1839 (Hoffmann, 2002). Despite this long history, hydrogen and fuel cell based energy systems are still some time away from becoming mainstream.

A number of countries and local initiatives have taken some first steps in attempting to make this idea a reality. Among these perhaps the most notable are Iceland and Japan. Iceland became the first country in 1999 to proclaim its goals of becoming a hydrogen economy by 2030 (Árnason & Sigfússon, 2000; Dunn, 2001). Japan on the other hand has set an ambitious goal of 50,000 FCV (fuel cell vehicles) and 2,200 MW for stationary fuel cells in 2010 and 15 million FCV and 12,500 MW for stationary fuel cells in 2030 (Fukuda, K., 2004; Fukuda, K., Kobayashi et al., 2001). The United States (State of California, 2004; US DOE, 2005a) as well as the European Commission (European Commission, 2003, 2005) has shown political support for the hydrogen and fuel cell movement. In addition to the individual countries mentioned above, the formation of the IPHE (International Partnership for the Hydrogen Economy) in 2003 (US DOE, 2003b) is testimony to the international effort underway in favour of establishing a hydrogen

economy. As yet, however, hydrogen has not made a significant contribution to the energy mix of any country.

Canada has been at the forefront of hydrogen and fuel cell developments at an international level. Ballard Power systems, a world leader in the developments of polymer electrolyte membrane fuel cells (PEMFC), Stuart Energy Systems, a leader in installations of hydrogen fueling stations worldwide, Powertech Labs, a leader in high pressure hydrogen storage tanks, Methanex, the world’s largest methanol producer, QuestAir Technologies, a leader in hydrogen purification and Westport Innovations, a developer of engines that run on hydrogen and/or natural gas, are just a sample of the Canadian expertise in this area. In addition, the Canadian hydrogen and fuel cell sector had its revenues grow 40% in 2003 over 2002, employment grew by 40% to 2,671 from the 2001 figures, participation in demonstration projects has increased 232% to 262 from 79 in 2002, and patent holdings are up by 34% to 581 in 2003 (Fuel Cells Canada, 2004).

The province of British Columbia in particular, over the past decade has been developing a critical mass in the fuel cells and hydrogen industry and is gaining reputation for its expanding hydrogen and fuel cells cluster. The selection of Vancouver as the venue for the 2010 winter Olympics was also a welcome boost for its hydrogen and fuel cells profile as the plan to build a “Hydrogen Highway™” between Victoria, Vancouver and Whistler received further endorsement (National Research Council Canada, 2004).
While many global and national energy scenarios have been constructed that show the long-term potential for hydrogen energy systems (European Commission, 2005; Feng, Wang et al., 2004; Fukuda, K., 2004; International Energy Agency, 2005; US DOE, 2002), it is not clear that most jurisdictions are on track to realize those scenarios. To date, most attempts to foster hydrogen energy systems on the ground have involved individual research, development or demonstration projects, focusing on individual hydrogen production or end-use technologies. Little attempt has yet been made to link these demonstrations to scenarios of future hydrogen contributions to the energy economy, and even less to assessing the characteristics and sustainability of such scenarios. In order to contribute to filling this gap, this paper focuses on developing a short-term (4 year) scenario of hydrogen production and consumption in British Columbia that builds on the demonstration projects being developed for the BC Hydrogen Highway between the cities of Victoria, Vancouver and Whistler. In addition to the scenario characterization, a first order sustainability assessment was conducted for the BC Hydrogen Highway™. Finally the results of the sustainability assessment are discussed and some suggestions made for future improvements in the area of sustainability assessments of energy systems.

2.2 Methodology

Data for this research was obtained primarily from members of the Hydrogen Highway Steering Team (HHST) - a consortium of professionals from industry, academia and government, established to manage the Hydrogen Highway™ project. Since many of the projects are still in the initial stages of development and some still in the process of receiving funding, considerable gaps were prevalent in the data obtained. However, in
order to keep the 2010 scenario as realistic as possible, care was taken not to make assumptions that were too optimistic. If large uncertainties existed with regards to the actual realization of the individual projects and if the impacts of the projects to the overall analysis were deemed insignificant, then those respective projects were not included in the analysis. Throughout the analysis, a number of energy related metrics were used to indicate the salient supply and demand characteristics of hydrogen, natural gas and electricity as well as the demand for fuel cells. Finally, for the sustainability assessment, National Resource Canada’s (NRCan) lifecycle emissions model, GHGenius 3.3, was used to suggest insights about the sustainability of the BC Hydrogen Highway™.

2.3 The BC Hydrogen Highway™ Project

The British Columbia Hydrogen Highway™ project was conceptualized by BC Hydro, Methanex Corporation and the National Research Council of Canada. It is a large-scale demonstration and deployment program intended to accelerate the commercialization of hydrogen and fuel cell technologies. The plan for 2010 is to develop a number of locations/nodes (see Figure 2-1) in the province of BC where the public and media can see, touch and feel the benefits of a hydrogen economy. In addition to providing a physical connection to these various nodes across the lower mainland, the Hydrogen Highway™ is a metaphor for the transition to a future hydrogen economy (National Research Council Canada, 2004). According to the Premier’s Technology Council (PTC), the goal of this project is to increase public and market awareness of hydrogen, fuel cell and related technologies during the 2010 Olympics (Connor, Britton et al., 2004). The province intends to use this international event to showcase the strengths and expertise of
the BC hydrogen and fuel cells industry cluster and to have the world’s pre-eminent hydrogen economy by 2020.

Figure 2-1: BC Hydrogen Highway™.

2.3.1 Nodes of the BC Hydrogen Highway™

The 7 nodes on the Hydrogen Highway™ (shown in Figure 2-1) as well as the supply and demand characteristics of their respective projects will constitute the main elements of the 2010 scenario. Although the projects at each node have different expected start dates between 2005 and 2010, and different durations of funding, the analysis used the available data to estimate the energy supply and demand profiles for the year 2010. The
hydrogen energy system defined in the scenario includes energy services derived from pure hydrogen, hydrogen rich natural gas (mostly CH₄) as well as hydrogen-enriched compressed natural gas (HCNG). It is also inclusive of different technologies such as fuel cells or internal combustion engines that can utilize hydrogen and/or natural gas to produce energy services.

2.3.1.1 The North Vancouver Node

The parent project at this node is called the Integrated Waste Hydrogen Utilization Project (IWHUP) (Sacre-Davey Innovations, 2004). The IWHUP consists of 7 sub-projects (see Figure 2-2). Of these, three projects (sub-projects 4, 5 & 7) constitute a demand for hydrogen, natural gas or fuel cells and one supplies hydrogen (sub-project 1). The remaining 3 involve the development and facilitation of the other projects and as such will be left out from this discussion as they do not impact the energy balance of the 2010 scenario.
Figure 2-2: Interrelations between the projects of the North Vancouver Node.

Of the 7 projects within IWHUP, sub-project 1 is the most significant. It involves the capturing of waste hydrogen from a chlor-alkali plant in North Vancouver, where currently hydrogen is vented at a rate of 600 kg/hr into the atmosphere. By initially capturing and processing 20 kg/hr, 24hrs/day for 7 days/week with an uptime of 92% (Sacre, 2005), the total annual hydrogen production will be approximately 161,184 kg (23,049 GJ). Depending on future demand the remaining 580 kg/hr is available for a later date.

Collectively the 7 sub projects at the North Vancouver node constitute a total annual demand of 6074 GJ (42,478 kg) for hydrogen and 4442 GJ for natural gas. The total fuel cell demand is 150 kW. It was assumed that the total demand for natural gas was met

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28 See www.clo2.com for the chemical processes involved at the chlor-alkali plant.
through the natural gas distribution grid in the province. As far as hydrogen supply and demand is concerned for this node, the hydrogen supply capability from sub-project 1 (23,049 GJ) far exceeds the total hydrogen demand (6074 GJ). This leaves sufficient room to supply the hydrogen demands of the other nodes.

2.3.1.2 The NRC-UBC Node

Much like the North Vancouver node, the NRC-UBC (National Research Council – University of British Columbia) node is an integrated hydrogen and fuel cell demonstration project, which brings together industry, academia and government agencies. The project will be promoted through an integrated communications program, building awareness and support among investors and the public, thereby accelerating the early adoption of this technology on a broader scale (University of British Columbia, 2004). Figure 2-3 shows the interrelations between each of the 5 projects.

For this node the total annual demand for hydrogen is 759 GJ (108 kg) and the total hydrogen supply capability is 1240 GJ (8670 kg). The total natural gas demand is 5260 GJ/yr while the total fuel cell demand is 605 kW.
2.3.1.3 The Surrey Node

This node has received funding for 3 different projects (Webster, 2004). In comparison to the North Vancouver node (H₂ - 5544 GJ, NG - 4422 GJ), the total hydrogen and natural gas demand for this node (H₂ - 62 GJ, NG - 416 GJ) is about one to two orders of magnitude smaller. The total demand for fuel cells at this node is only 70 kW (from 1 fuel cell vehicle). As such the results from this node are not expected to affect the overall energy balance of the 2010 scenario.

2.3.1.4 The Vancouver and Vancouver Airport [YVR] Nodes

The Vancouver node does not have any funding or proposals for funding to date, as the projects are currently in the concept phase. In the interest of keeping the 2010 hydrogen energy scenario as realistic as possible and since the concept projects are not expected to significantly alter the results of this analysis it was decided to leave out this node from the overall analysis.
The main project at the Vancouver Airport node is a hydrogen fueling station (Patrick, 2005), which is expected to be operational in spring 2006. The total annual hydrogen supply of this node is estimated to be about 1240 GJ (8670 kg). The electricity demand for the onsite electrolyzer (for hydrogen production) will be approximately 505 MWh_e.

2.3.1.5 The Victoria Node

This node will demonstrate a mobile hydrogen fueling station. Currently the project is still in the concept phase (HHST, 2005). It is estimated that the electrolyzer which will produce the hydrogen for the mobile fueler would produce 20kg/day (9 Nm^3/h) or 992 GJ/yr (6935 kg/yr). This would be sufficient for 4 fueling events per day (at 5kg each) and can support the equivalent of a fleet of 36 Fuel Cell Vehicles. The annual electricity consumption for the electrolyzer^{29} will be approximately 380 MWh_e or 1360 GJ.

2.3.1.6 The Whistler Node

The 2 main projects of this node are (a) the hydrogen and fuel cell powered transit bus project (15-25 FC buses) and (b) the stationary Fuel Cell or CHP (combined heat and power) demonstration at the Olympic Athletes Village and/or Visitor’s center (HHST, 2005). Although these projects are still in the concept phase leaving them out of the analysis would be inappropriate given that Whistler is the venue for the 2010 winter Olympics and given the magnitude of the contribution they will have to the overall energy demand. The importance of this statement will be evident later in the analysis. As

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^{29} Assumptions: Stuart Energy Electrolyzer with daily H2 production of 20 kg, 9 Nm^3/h, 4.8 kWh/Nm^3, 95% availability factor; 4 fueling events per day (5kg each) and a refueling frequency of once every 9 days; 5% premium for compression included in calculations.

^{30} To be conservative, only 9 buses were assumed for the analysis.
the details of the above-proposed projects are not available yet, assumptions had to be made where necessary.

Given the assumptions in Table 2-1 (adapted from the CUTE projects in Europe (CUTE, 2003, 2004)), the buses would annually require a total of 118,260 kg of hydrogen (16,911 GJ). It was assumed that the buses will be refueled at the North Vancouver node, given the large hydrogen supply at that node. By carefully planning the logistics of hydrogen supply and demand between these two nodes, the large costs of installing a large electrolyzer at the Whistler node could be eliminated.

<table>
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<th>Value</th>
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<td>Operating range [km]</td>
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<td>Distance Travelled per day [km]</td>
<td>250</td>
</tr>
<tr>
<td>Hydrogen on-board [kg]</td>
<td>40</td>
</tr>
<tr>
<td>Number of Buses</td>
<td>9</td>
</tr>
<tr>
<td>Availability factor</td>
<td>0.90</td>
</tr>
<tr>
<td>Number of Refuelling events per day</td>
<td>1</td>
</tr>
<tr>
<td>Total Annual Hydrogen demand [kg]</td>
<td>118,260</td>
</tr>
<tr>
<td>Total Annual Hydrogen demand [GJ]</td>
<td>16,911</td>
</tr>
<tr>
<td>Total FC demand [kW]</td>
<td>1,845</td>
</tr>
</tbody>
</table>

Table 2-1: Assumptions and Calculations for the Whistler Transit Bus Project.

As far as the CHP demonstration project is concerned, it was assumed that a 250 kW Molten Carbonate Fuel Cell (MCFC) operating in CHP (combined heat and power) mode, would provide electricity and heat. It was estimated that the 250 kW unit would consume approximately 16,463 GJ of natural gas (from the grid) and produce approximately 7488 GJ (2080 MWhₑ) of electricity and 4478 GJ (1244 MWhₜ) heat on an
annual basis. According to these figures, the electrical and thermal efficiencies are 45% and 27% respectively (overall system efficiency is 72%).

In summary, the 2010 energy scenario for this node would consist of a total demand for hydrogen of just under 17,000 GJ, for natural gas about 16,500 GJ and for fuel cells just over 2 MW. All the hydrogen demand and most of the demand for fuel cells, come from the transit bus project. The estimated cost of hydrogen production from electrolysis, based on an electricity rate of $0.07/hr in BC, is approximately $4/kg. The cost for hydrogen capture at the North Vancouver node is not presently known, but is expected to be a fraction of this cost.

### 2.4 Energy Balance

Table 2-2 below provides a qualitative summary of the various projects that constitute the BC hydrogen energy scenario in 2010. It shows the various sources for demand and supply for energy as well as fuel cell demand. The column denoted “Other”, represents projects that play a role of support and facilitation or are in the concept phase.
<table>
<thead>
<tr>
<th>Node/Project</th>
<th>H₂</th>
<th>NG</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>North Vancouver Node</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Hydrogen Capture</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressed Gas Storage</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mobile Hydrogen Fuelling Station</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Translink Bus Project</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Light Duty H₂ powered ICE vehicles</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facilities for Fuelling Buses</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fuel Cell powered Carwash</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>NRC-UBC Node</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂ Fuel Cell backup power generator</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Westport Heavy vehicles</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>5 kW SOFC Demonstrations</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Vancouver Fuel Cell Vehicle Project</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>BOC Hydrogen Fuelling Station</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Surrey Node</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCNG vehicle project</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>BC Hydro Ford FCV</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>H₂ Direct Combustion</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>H₂ production, storage and dispensing</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>Vancouver Node</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuelling demonstration at CNG site</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>CIRS - Stationary, portable and other demonstrations</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Biogas feedstock for fuel cells</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>Vancouver Airport (YVR) Node</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂ fuelling station</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mobile off-road equipment demonstration</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mobile in-terminal demonstrations</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>Victoria Node</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile H₂ fueller and station</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>Whistler Node</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC Transit Bus project</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Stationary FC and CHP demonstration</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mobile off-road vehicle demonstration</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 2-2: Qualitative summary of the 2010 BC hydrogen energy scenario.

Table 2-3 is a more quantitative summary of the BC hydrogen energy scenario. It specifies the overall demand for hydrogen, natural gas and fuel cells, as well as the hydrogen supply capability for the entire Hydrogen Highway™ in 2010. As can be seen
from this table, the Whistler node makes up most of the demand for hydrogen, natural gas and fuel cells, while the North Vancouver and NRC-UBC nodes make up only a small fraction. The total hydrogen supply capability of the Hydrogen Highway™, based on the assumptions made, is 26.6 TJ while the total hydrogen demand is only 23.8 TJ. Hence, the hydrogen supply capability of all the nodes is about 10% greater than the estimated demand.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>North Vancouver</td>
<td>42,478</td>
<td>6,074</td>
<td>4,442</td>
<td>150</td>
<td>16,911</td>
<td>71.0</td>
<td>16,463</td>
<td>71.0</td>
<td>161,184</td>
<td>23,049</td>
<td>86.7</td>
</tr>
<tr>
<td>NRC-UBC</td>
<td>5,308</td>
<td>759</td>
<td>5,260</td>
<td>605</td>
<td>8,670</td>
<td>20.7</td>
<td>434</td>
<td>2.4</td>
<td>8,670</td>
<td>1,240</td>
<td>4.7</td>
</tr>
<tr>
<td>Surrey</td>
<td>434</td>
<td>62</td>
<td>416</td>
<td>70</td>
<td>434</td>
<td>2.4</td>
<td>434</td>
<td>2.4</td>
<td>8,670</td>
<td>1,240</td>
<td>4.7</td>
</tr>
<tr>
<td>Vancouver</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Vancouver Airport</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Victoria</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6,935</td>
<td>992</td>
<td>3.7</td>
</tr>
<tr>
<td>Whistler</td>
<td>118,260</td>
<td>16,911</td>
<td>16,463</td>
<td>2,095</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>166,479</td>
<td>23,806</td>
<td>26,581</td>
<td>2,920</td>
<td>185,893</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>26,583</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 2-3: Energy Balance of the 2010 BC Hydrogen Highway™.

Table 2-3 also shows that the North Vancouver node is responsible for the vast majority of the hydrogen supply. The hydrogen production at 20 kg/hr, from the waste hydrogen stream (Project 1 North Vancouver node), amounts to about 23 TJ. This project alone can meet the hydrogen demand for about 96% of the total annual hydrogen demand. As such the waste hydrogen capture project represents one of the most significant projects on the BC Hydrogen Highway™, not to mention its sustainability benefits which will be discussed in the next section.

The projected total energy demand for BC in 2010 is approximately 1,350 PJ (National Energy Board, 2003). Of this, the demand for natural gas alone is about 300 PJ while that
for electricity is about 280 PJ. The Techno-Vert scenario of the National Energy Board (NEB) scenarios, project a hydrogen energy demand of 680 TJ for BC in 2010. However, the hydrogen demand for the BC Hydrogen Highway™ (23.8 TJ) is only about 3.5% of this projected demand (680 TJ). As such, when taken together, the seven nodes of the Hydrogen Highway™ will produce and use negligible amounts of hydrogen and will not by themselves give rise to a significant penetration of hydrogen and fuel cell technology into the BC energy system. If BC is to achieve the levels of hydrogen production and use envisaged in the “high hydrogen” NEB scenarios (Techno-Vert) by 2010, substantial new efforts, in addition to those associated with these seven nodes, will be required. The implications of this will be discussed further in the final section.

To summarize, the 2010 hydrogen energy scenario for BC can be characterized by four energy parameters: (a) hydrogen demand = 23.8 TJ (b) natural gas demand = 26.6 TJ (c) fuel cell demand = 2.9 MW (d) Hydrogen Supply = 26.6 TJ. The above energy parameters provide a good heuristic measurement for the extent and magnitude of the BC Hydrogen Highway™. Based on the complexity of a given hydrogen energy system, similar energy parameters for coal, coal bed methane, biogas, methanol, electricity etc., may also be used. Such energy parameters may be used for the purpose of cross-comparisons between future hydrogen based energy systems.

2.5 Sustainability Assessment

Of course the energy balance of the BC Hydrogen Highway™ does not provide any indication of its sustainability. However, given the uncertainty involved with many of the smaller projects (and their small contributions) a detailed sustainability assessment of all
projects would provide marginal insights at best. But given the somewhat disproportionate nature of the various projects, interesting insights regarding the sustainability of the Hydrogen Highway™ project can be gleaned by focusing on a few select projects. On the hydrogen supply side, the waste hydrogen capture project (Project 1 North Vancouver node) represents almost 97% of the entire hydrogen supply while on the hydrogen demand side the Transit bus project at the Whistler node represents over 70% of the total demand. As such, for a first-order analysis, a sustainability assessment that incorporates these 2 projects would provide reasonable insights into the sustainability of the BC Hydrogen Highway™.

Sustainability is often difficult to define and since it encompasses a wide range of ideas from different disciplines it is not easily reducible to a single unit. A meaningful sustainability assessment therefore must be comprehensive and also take into account the values of the stakeholders involved. This paper does not pretend to conduct such a comprehensive sustainability assessment, but will attempt to provide insights concerning various aspects of sustainability for the BC Hydrogen Highway Project, in terms of some economic, social, environmental and technical criteria.

Any sustainability assessment must invariably incorporate a life cycle perspective. Natural Resources Canada (NRCan) has developed a lifecycle emissions model called GHGenius, for the purpose of modeling various transportation technologies and fuels ((S&T)2 Consultants Inc., 2005b). In this study, GHGenius was used to draw insights about the life cycle performance (and thus sustainability) of the most significant projects
of the 2010 BC Hydrogen Highway. The criteria used for the sustainability assessment were based on the outputs that were available from this model. Therefore the criteria used below to assess sustainability of the Hydrogen Highway, such as the various green house gas and air pollutants emissions, cost-effectiveness and energy efficiency parameters were a direct result of modeling the Hydrogen Highway in GHGenius.

2.5.1 Results of the Sustainability Assessment

GHGenius measures life-cycle CO₂(eq) based on a combination of carbon-dioxide, methane and nitrous-oxide and their relative global warming potentials. This includes the emissions from the fuel-cycle as well as from the vehicle production phase. Figure 2-4 shows the life-cycle CO₂(eq) emissions for the Whistler transit bus along with its natural gas and diesel counterparts. The hydrogen for the fuel cell buses is assumed to be supplied by the waste hydrogen capture project in North Vancouver (the Hydrogen Highway's largest hydrogen supplier). The efficiency of the waste hydrogen capture and compression is assumed to be approximately 90% (Armstrong, 2006) in 2010. As shown in Figure 2-4 the life cycle CO₂(eq) emissions of the fuel cell transit buses powered by a waste stream of hydrogen would be approximately 70% below its diesel and natural gas counterparts. Most of this gain is achieved through virtually zero CO₂(eq) emissions in the vehicle operation phase.

---

31 The 100 year global warming potentials used are: CO₂ = 1; CH₄ = 21; N₂O = 310
32 It is worth noting that for the fuel cell buses although tail-pipe emissions are virtually zero, that the upstream and vehicle production related emissions are in par with the diesel and natural gas buses. However, as far as Climate Change and its impacts are concerned the spatial distribution of CO₂ emissions is of no consequence – it is the total reduction that really matters.
Comparison of Life Cycle CO2 (eq) Emissions for Fuel Cell Bus with Conventional Buses

**Figure 2-4: Life Cycle CO2(eq) emissions of various bus technologies.**

Although CO2(eq) is a good proxy for the impacts of a technology on climate change, it does not address the local impacts of the air pollutants that affect society more directly. The increase of ground level ozone (GLO3) formed by particulate matter (PM), volatile organic compounds (VOC) and nitrogen oxide (NOx) need to be part of a sustainability assessment, due to their resulting impact on mortality (and morbidity) from respiratory and cardiac illnesses (National Research Council, 2002). Figure 2-5 shows the absolute and relative lifecycle air pollutant emissions for the fuel cell bus (powered from a waste stream of hydrogen) as well as for natural gas and diesel buses. In the upstream and vehicle production phases the fuel cell bus (FCB) has comparable emissions to its NG

---

33 Whether PM, VOC and NOx all need to be part of the analysis or if just one of these pollutants can be used as a reasonable proxy for their combined impacts is still somewhat uncertain, due to the complexity of ozone formation and its ultimate societal impacts. All 3 have been shown here as in general an increase in any one or all are not a desirable outcome.

34 It should be noted that the cumulative total of each bar on the chart is not of any consequence. It is the relative magnitude of each technology that should be compared.
and diesel counterparts while in the vehicle operation phase it has virtually zero emissions across all air pollutants. Although the spatial distribution of CO$_2$(eq) is not critical as far as health impacts are concerned, the spatial distribution of local air pollutants are very important. As such the FCB has a superior performance across all the pollutants shown in Figure 2-5.

![Figure 2-5: Life Cycle Air-Pollutant emissions of various bus technologies.](image)

Figures 2-4 & 2-5 show the performance of the whistler FCBs in terms of concerns about climate change and societal health impacts. GHGenius was also used to compare the cost-effectiveness (CE) of FCB against its diesel counterpart. The measure of cost-effectiveness is used to reconcile the CO$_2$(eq) reductions from a given technology against
the lifecycle costs of that technology. The most important lifecycle costs that affect the CE are the relative lifecycle fuel costs and relative fixed vehicle costs, per unit of CO₂(eq) reduction (S&T)2 Consultants Inc., 2005a). The effect of these costs on the CE value is shown in Table 2-4. As shown, a reduction in the fuel stack cost of $99,558, an increase of the crude oil price by $42.6 per bbl, and a reduction in the final delivered price of hydrogen of $2.50 all have the same impact of improving (reducing) the value of CE. Assuming $75 per barrel of crude-oil, a premium of $200,000 for the fuel cell stack and a hydrogen cost of 10 $/kg, the CE for the FCB is 354 $/ton of CO₂(eq) reduced.

Although the FCB has much lower emissions (Fig 4 & 5) compared to its diesel and natural gas counterparts, it is not a cost-effective means of reducing CO₂(eq) at today's price of carbon. Given that the BC hydrogen Highway is a demonstration project this is not a surprising result, as they do not have the benefit of large markets and economies of scale. However, in the future, based on the annualized vehicle and fuel costs, and the price of carbon the CE could be quite different.

<table>
<thead>
<tr>
<th>Parameter (X)</th>
<th>Change in X per $100/ton improvement (reduction) in CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Stack Price</td>
<td>- 99,558</td>
</tr>
<tr>
<td>Crude Oil Price</td>
<td>+ 42.6</td>
</tr>
<tr>
<td>Cost of delivered</td>
<td>- 2.5</td>
</tr>
</tbody>
</table>

Table 2-4: Sensitivity of Cost-effectiveness for Fuel Cell Buses.

Another relevant metric for the sustainability assessment is the amount of energy consumed per km driven - this is a measure of the energy efficiency of a given pathway.

---

35 The smaller the Cost-effectiveness value (in $/ton CO₂(eq) saved) the better, as it implies a lower cost of CO₂(eq) reduction.

36 In addition to these parameters the following values were used in the calculation of CE. They are: relative fuel cell efficiency compared to a diesel engine = 1.72; economic lifetime = 10 yrs; distance traveled in economic lifetime = 1,092,293 km; social discount rate = 5%; private discount rate = 1%; emissions discount rate = 3%.
Table 2-5 shows the results from GHGenius for this parameter. As can be seen the total energy consumed per km for the FCB, powered by hydrogen from a waste source, is about 50% of that of the diesel and natural gas buses. This is attributed largely to the higher efficiency of the fuel cell.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Diesel ICE Bus [kJ/km]</th>
<th>Natural Gas ICE Bus [kJ/km]</th>
<th>Waste Hydrogen Fuel Cell Bus [kJ/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>End use</td>
<td>19250</td>
<td>23772</td>
<td>9270</td>
</tr>
<tr>
<td>Fuel dispensing</td>
<td>35</td>
<td>348</td>
<td>603</td>
</tr>
<tr>
<td>Fuel distribution, storage</td>
<td>83</td>
<td>633</td>
<td>1561</td>
</tr>
<tr>
<td>Fuel production</td>
<td>1893</td>
<td>951</td>
<td>1289</td>
</tr>
<tr>
<td>Feedstock transmission</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Feedstock recovery</td>
<td>3325</td>
<td>251</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>24606</td>
<td>25955</td>
<td>12723</td>
</tr>
</tbody>
</table>

Table 2-5: Energy consumed per km for different bus types.

2.5.2 Uncertainties in the Sustainability Assessment

The above analysis provides some clues regarding the sustainability of the BC Hydrogen Highway™. By focusing the analysis on the largest projects, it appears that as a whole the entire project is far more sustainable in terms of its CO₂(eq) emissions, air pollutant emissions and energy efficiency but costly in terms of its CO₂ reduction potential. Although the cost-effectiveness measured here was based on the importance given to the price of carbon emissions (i.e. climate change) it did not include the costs of mortality (and morbidity) induced from air pollution. A more comprehensive cost-effectiveness analysis should include costs of air pollution induced mortality as a separate metric or combined in the total cost-effectiveness calculation. Also as mentioned above,

37 In GHGenius this output does not include the energy consumed in the vehicle manufacture stage and as such it is a proxy for the energy efficiency of the fuel-chain only. Since the energy and material requirements for the production of the fuel cell are very different, ideally it should be included in this calculation.
technologies that have a desirable spatial distribution of air pollution (i.e., zero or low emissions in urban areas) in addition to having low air pollution should be credited accordingly.

In addition to greenhouse gases and local air pollutants the lifecycle of fossil powered automobiles are also responsible for the release of a significant amount of carcinogenic toxic chemicals such as benzene, acetaldehyde, formaldehyde and 1,3 butadiene (MacLean, Heather L., Lave et al., 2004). A sustainability assessment should also take into account such emissions due to their disproportionately greater impacts on human health. However, this was beyond the scope of this analysis.

One of the limitations of GHGenius is that the transmission system of the fuel cell bus (or other fuel cell vehicle) is modeled similar to a regular internal combustion engine (ICE). Since the construction of a fuel cell requires different materials (some of which are fairly energy intensive) the embodied emissions and energy of the fuel cell stack itself could be much higher than a generic ICE. As significant improvements are made in energy and emissions reductions in the vehicle operation phase, it becomes increasingly critical to accurately model the energy and emissions from vehicle manufacture, as its share in the life cycle energy and emissions increase rapidly. However, there is a serious lack of information available regarding the fuel cell construction process (Pehnt, 2001) which is perhaps the reason for this omission in GHGenius. As such, the modeling of the emissions and energy from the vehicle manufacturing phase for the FCB, are perhaps underestimated.
Finally a sustainability assessment should preferably translate all emissions into measurable impacts, while taking note of the considerable heterogeneity in the way emissions impact humans. In addition to the significance of spatial distribution, perhaps temporal distribution of emissions can also be significant, especially when considering the formation of photochemical-smog. Final impacts are a result of not just ambient concentrations (emission levels) but also exposure and toxicity. As alluded to above, the uncertainties involved in sustainability impact assessment are many, hence a comprehensive sustainability assessment must be open to its limitations so that as information becomes available and as the state of knowledge improves, so will the science of sustainability (Swart, Raskin et al., 2004).

2.6 Concluding Remarks

One of the objectives of this study was the characterization of a real life demonstration hydrogen energy system in 2010 - the BC Hydrogen Highway™ Project. In terms of hydrogen, the demand in the BC 2010 scenario is only about 3.5% (23.8 TJ) of the projected demand for hydrogen in the NEB Techno-Vert Scenario (680 TJ) - which in itself is only 1/2000th of the total energy demand in 2010 (1350 PJ); this points to a significant disjuncture between current demonstration projects and a future energy system worthy of being called a “hydrogen energy system”. In terms of hydrogen energy demand, although the BC Hydrogen energy scenario for 2010 is between the NEB Supply-Push Scenario (0 TJ of hydrogen energy and no fuel cells) and the Techno-Vert Scenario (680 TJ), the 23.8 TJ of the BC Hydrogen scenario in 2010, is a lot closer to the
Supply-Push scenario of no hydrogen and fuel cells than the more optimistic Techno-Vert scenario.

Bridging the chasm between current efforts and the Techno-Vert hydrogen demand projections for 2010 itself would be a colossal undertaking - even without the projected 21% annual increase for the period 2010-2020 in the NEB Techno-Vert scenario. Based on the insights revealed from this study, the current rate of activity seems insufficient to meet the NEB scenario projections for 2020, unless current activity is ramped up several-fold. Therefore, the question becomes less about ‘whether the 2020 goals will be reached’ and more about ‘when?’ As such, reaching this goal in a timely fashion will require some explicit thought and detailed planning by the hydrogen and fuel cell community in British Columbia. The BC Hydrogen and Fuel Cell Strategy (Connor, Britton et al., 2004) presents a clear ‘vision’ of a future hydrogen economy in BC by 2020. Although, visioning is an important and necessary step, the challenge lies in the development of a realistic plan which is based on the acknowledgement of the current state (which begins by first characterizing it – an objective of this paper), visualization of an ‘achievable’ future state and construction of a path (or plan) that bridges the present with the future.

The technology diffusion literature provides many examples of superior technologies failing to make the transition from innovation to actual diffusion due to various path-dependent phenomena that can favour the diffusion of technologies that are somewhat inferior, due to random historical events (Arthur, Brian W, 1989; Loch & Huberman, 1999). No grand-unifying-theory of technology diffusion has yet emerged – this is due
largely to the many confounding effects characteristic not only of the novel technology
(innovation) but which are a result of the nature and large time-constants of the
‘technology lock-in’ that is characteristic of the energy sector (Grubler, Nakicenovic et
al., 1999) and the socio-economic, political and institutional context within which the
novel technology is attempting to diffuse. (Geels, Frank W. & Smit, 2000) discuss a
number of lessons that can be learned from a survey of failed technology futures. For
instance they argue that the inability to account for, cultural shifts within society, co-
existence of old and new technologies and the co-evolution of technology and society
may help explain some of the discrepancy between future expectations and actual
technological development (or lack thereof) and societal impact. Thus, when constructing
the path/plan between the present and the future, it is imperative for proponents of any
new technology (including those for hydrogen and fuel cells) to fully appreciate the
insights and dynamics of technology diffusion discussed above.

The second goal of this paper was to conduct a first-order sustainability assessment of the
hydrogen energy system for British Columbia in 2010. The results of the sustainability
assessment (based on a life cycle perspective) showed the superior performance of the
BC Hydrogen Highway™ projects in terms of its low CO\textsubscript{2}(eq) and air pollutant
emissions, as well as energy per unit of service delivered. However, the cost-
effectiveness analysis revealed a cost of approximately $350 per ton of CO\textsubscript{2}(eq) saved\textsuperscript{38}. The lifecycle emissions model (GHGenius) used for the cost-effectiveness calculations
were based on the cost per tonne of GHG saved. The limitation of such a metric is that it
places the entire burden of cost-effectiveness on the price of carbon and does not spread

\textsuperscript{38} Such high values for cost effectiveness are not surprising for early stage technologies.
the costs over realized benefits other than just CO$_2$ reduction. Most experts would agree that carbon savings is not the only benefit that matters. If this is widely accepted, then it is imperative to recognize that such a metric is only a partial calculation and as such is likely to reveal only partial insights. The reason for the use of such metrics of limited scope is perhaps the ease of calculation of CO$_2$ savings or the significance placed globally on climate change. In the future, other quantifiable benefits should also be included in the cost-effectiveness calculation. However, since not all benefits are easily quantifiable, this points to the importance of a sustainability assessment based on the principles of multi-criteria assessment which permits the inclusion of criteria that are both quantitative as well as qualitative.

Analyses of the diffusion of large scale technologies and infrastructures reveal that the time-constants for diffusion are between 5-10 decades (Grubler, Nakicenovic et al., 1999). As such, the importance of early investment, in order to take advantage of the cumulative learning effects, cannot be over emphasized. In addition, since the body of evidence in the technology diffusion of the energy sector suggests that it is mostly due to induced technical changes rather than autonomous technical changes (Grubb, Kohler et al., 2002), the demonstration of sustainability will be a crucial factor in inducing the large investments necessary for the highly uncertain and radical technologies such as hydrogen and fuel cells.
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3 Sustainability Assessment Exposed – a framework for designing the next generation of Assessments

3.1 Introduction

The notion of sustainability, its multi-disciplinary components (economic, environmental and social elements), the complexities arising from the interaction of these components (i.e. coupling, feedbacks), its inter-temporal (i.e. intergenerational equity) and spatial (i.e. intra-generational impacts) characteristics and above all the significance of its context, have been widely discussed in the literature over the past two decades. The practice of assessment (i.e. economic, life-cycle, environmental) enjoys a longer history and often consists of well developed methods applied within a variety of disciplines. However, combining the complex notion of sustainability with the practice of assessment is not a straightforward process and presents some interesting conceptual and practical challenges.

An important feature of sustainability is that it encompasses quantitative as well as qualitative information. Given that quantitative information may be more relevant and appropriate in some disciplines (i.e. engineering, economic) while qualitative information is the norm in others (social sciences) at the very outset ‘sustainability assessment’ demands an approach that can incorporate both information types. Also a number of conceptual challenges also exist for sustainability assessment; such as issues of scale, systems complexity, incommensurability, equity, problem framing, uncertainty, knowledge gaps etc.

39 A version of this chapter has been submitted for publication to the International Journal of Sustainable Transportation.
Another important challenge has to do with the suitability of sustainability assessment tools and the process of their selection. Over the years different disciplines developed tools and methods of assessment that suited their disciplinary focus and interests, fairly independently of each other. For instance, while some developed tools and methods to account for flows of physical data (i.e. material, energy used in Material Flow Analyses and Life Cycle Analyses) within an economy, others developed tools that were consistent with monetary (or monetizable) data (i.e. Cost-Benefit Analysis, Green Accounting).

Similarly in order to deal with qualitative information qualitative methods such as Focus Groups and qualitative scenarios have been developed. Acknowledging the importance of these various types of information for policy analysis, more recently methods or tools such as Multi-Criteria Analysis, Integrated Modelling tools, Scenario Analysis and participatory processes have emerged.

However, even these more recent methods/tools have their own pros and cons. Furthermore it is important to note that none of the tools were actually developed for the assessment of sustainability, although each of them captures significant aspects of it. Given the multiplicity of available tools and the complexity of sustainability assessment, a framework is needed that guides the sustainability assessment practitioner with the selection of appropriate tools for the design of a given sustainability assessment. Such a framework would ideally guide the tool selection process such that the eventual analysis compensates for the sustainability and methodological blind-spots of any given tool.
With these issues in mind, this paper will propose a framework to aid with the challenge of tool selection for sustainability assessments. While this is one of many challenges facing the sustainability assessment practitioner, the framework will be discussed in the context of the other conceptual and practical challenges of sustainability assessment.

In the next section we will discuss what sustainability assessment tools are and what has been said about them in the literature. Section 3.3 will then develop and propose a framework for tool selection and propose the ‘Integrated Assessment approach’ and ‘Multi-Criteria Analysis process’ as the core tools necessary for selecting the other tools for a given sustainability assessment.

Section 3.4, will delve into some of the main conceptual challenges associated with sustainability assessment, such as issues of scale, complexity, equity, problem framing, uncertainty, knowledge gaps etc. This will be followed by a discussion in section 3.5 on the relevance of these conceptual challenges to the proposed framework. Ideally an Integrated Assessment would include stakeholder engagement, however, that is beyond the scope of this analysis. Nevertheless in section 3.6, a preliminary application of an integrated assessment within a multiple criteria (both quantitative and qualitative) process (for an example from the transport sector), will serve as an illustration on how to select appropriate tools and methods for sustainability assessments. This process will also reveal a number of ancillary insights regarding the specific problem being analyzed. Section 3.7 will discuss some practical considerations for sustainability practitioners and close with the main conclusions from this study in section 3.8.
Commenting on the importance of Integrated Sustainability Assessments (ISAs at the international level) (Rotmans, J., 2004a) points to the limitations of the current portfolio of tools and the need for a new generation of tools capable of accommodating multiple dimensions of sustainable development, multiple scales, multiple domains and multiple generations. We hope that the sustainability assessment framework proposed here and its facilitation with the tool selection process will contribute toward developing the building blocks necessary to support the next generation of assessments – sustainability assessments.

3.2 Sustainability Assessment Tools

3.2.1 The challenge of selecting Tools for Sustainability Assessment

There is a multitude of tools available for assessment purposes. The problem is that each of these may be used for a variety of different assessments. This creates confusion for the tool selection process and for the design of the sustainability assessment - as any combination of tools may be chosen by the practitioners (depending on their particular inclinations and preferences for tools). Thus different groups of practitioners may select entirely different sets of tools for the same sustainability problem.

Such heterogeneity and freedom in tool selection could render the comparisons of results or policy insights generated from different assessments of a given problem, or different assessments across different problems, difficult at best. It is not surprising that different sustainability problems would demand different sets of tools, but if there is a method to the selection then it may appear less hap-hazard and comparisons become more
manageable and meaningful. It is expected that the framework proposed here would contribute to the choice of tool selection across a multitude of problems.

Although different problems would require different tools for sustainability assessment, it is perhaps conceivable that there may be a core set of tools that would appear in most if not all sustainability assessments, while the balance would be context dependent. Commenting on the essentials of sustainability assessment (Gibson, Hassan et al., 2005) suggest a similar duality to sustainability assessment, whereby the universal aspect (the core or common ground) would lead to general sustainability criteria applicable across all assessments and the context dependent nature would command particularities specific to the problem, region etc. Such a duality will be useful in developing the sustainability assessment framework, in section 3.3.

3.2.2 Tool Integration and past Sustainability Assessment approaches

The literature provides numerous reviews of assessment tools/methods including the manner in which they've evolved or influenced each other over the years (Brunner & Starkl, 2004; de Ridder, 2005; Hajkowicz, Young et al., 2000; Hobbs & Meier, 2000; Rabl, Zoughaib et al., 2004). Amongst these, the SustainabilityA-Test\textsuperscript{40} (de Ridder, 2005) provides by far the most comprehensive review and evaluation across a wide spectrum of tools.

\textsuperscript{40} The SustainabilityA-Test is a recent European Commission study undertaken to compare and evaluate over 50 assessment tools and methods within a common framework for their relevance to sustainability.
Recognizing that different tools have different strengths and weaknesses, a number of experts have suggested the importance of tool integration for assessment purposes (Bell, Hobbs et al., 2003; Giampietro, Mario, Mayumi et al., 2006; Hajkowicz, Young et al., 2000; Løken, 2007; Polatidis, Haralambopoulos et al., 2003). In the context of energy systems and their sustainability (Polatidis, Haralambopoulos et al., 2003) suggests a framework consisting of Integrated Assessment (IA), Transition Management (TM) and Multi-Criteria Assessment (MCA) due to their complementing features and collective ability in capturing the essence of sustainability. Similarly, (Giampietro, Mario, Mayumi et al., 2006) while arguing the irreducibility of criteria (technical and social incommensurability) and recommending caution against single ‘best solutions’, suggest an approach for sustainability that includes Participatory Integrated Assessment (PIA) in combination with Multi Criteria Analysis (MCA).

While stressing the importance of qualitative data and stakeholder participation for sustainability assessments (Brunner & Starkl, 2004) proposes an axiomatic approach to tool selection (referred to as decision support methods) based on axioms from social welfare theory. While not recommending any particular tool, they emphasize the importance of transparency that this approach offers and of communicating to stakeholders the pros and cons of the decision making process. (Hajkowicz, Young et al., 2000) while reviewing decision support techniques for natural resource management makes a distinction between policy frameworks (Life Cycle Assessment, Risk Assessment, Social/Environmental Impact Assessment) and analytical techniques (i.e.
BCA, MCA methods). They describe policy frameworks as being flexible and adaptable to a wide range of settings in which they are applied and analytical techniques as following more rigid and repeatable procedures which can be applied within a given policy framework. While acknowledging the limitations inherent within all tools/techniques, they emphasize the value of MCA methods and their applicability with most policy frameworks.

The general message above was that no one tool on its own emerges as being powerful enough and widely applicable to be suitable for sustainability assessments, and therefore integration is necessary. While no tool dominates the universe of tools, IA and MCA seem to emerge as valuable components of a sustainability assessment. In section 3.3, IA and MCA will be further decomposed to expose their underlying philosophical and analytical components, as this distinction will be important for the development of the sustainability assessment framework.

41 The different policy frameworks are considered to be alternative procedures for handling particular aspects of the natural resource management decision problem. Therefore, depending on one's problem interest one would choose between 6 policy frameworks (environmental impact assessment, social impact assessment, risk assessment, urban and regional planning, citizen juries and life cycle assessment) and apply specific analytical techniques within the chosen framework. The goal is not sustainability assessment, but assessment of a particular aspect of sustainability.

42 Detailed descriptions of the different tools/methods will not be repeated here, in the interest of avoiding repetition. For a review of the different tools the reader may refer to the literature discussed in the above two paragraphs.
3.2.3 The Universe of Assessment Tools

The SustainabilityA-Test has created an inventory of over 50 assessment tools and methods currently in use, and grouped them into 7 tool-families. These tool families are (1) Physical Assessment Tools (2) Monetary Assessment Tools (3) Modelling Tools (4) Scenario Analysis (5) Multi-criteria Assessment (MCA) Tools (6) Sustainability Appraisal Tools and (7) Stakeholder analysis tools. Table 3-1 provides a summary of the various tools and methods within each tool family. Although not exhaustive this list is fairly comprehensive. Therefore, collectively they will represent the universe of tools for the following discussion.
<table>
<thead>
<tr>
<th>Physical Assessment</th>
<th>Monetary Assessment</th>
<th>Modelling</th>
<th>Scenario Analysis</th>
<th>Multi-Criteria Assessment</th>
<th>Sustainability Appraisal</th>
<th>Stakeholder Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterizing lifestyles and their resource consumption (CLARC)</td>
<td>Genuine Savings – GA_M3</td>
<td>Demographic Models – SEM_3</td>
<td>NAIADE – MCA_M6</td>
<td>- MCA_M6</td>
<td>TIDDD</td>
<td></td>
</tr>
<tr>
<td>Land-use Models – IM_1</td>
<td>Integrated Assessment Models – IM_2</td>
<td></td>
<td>- MCA_M4</td>
<td>- MCA_M4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qualitative Systems Analysis – IM_3</td>
<td>Scenario Building and Planning – IM_4</td>
<td></td>
<td>- MCA_M4</td>
<td>- MCA_M4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-1: SustainabilityA-Test Tools – adapted from de Ridder (2005).
In Table 3-1 the number of permutations\footnote{Since the order of tool-nesting can result in non-equivalent combinations, in other words since the order matters, we use the term ‘permutation’ as opposed to ‘combination’ (where order is inconsequential). As an example, a given result from using LCA within a CBA framework might be quite different from the result if the nesting was reversed.} in which the various tools and methods may be combined is quite large. However, permutations based on any arbitrary selection of tools from this tool-space may not lead to a sustainability assessment\footnote{reminding us of the garbage in garbage out phenomena (Funtowicz and Ravetz 1990; Munda 2005).}. The next section will propose some minimum requirements for tools and provide some guidance for designing sustainability assessments. But first, let us take a look at an example where a number of tools from Table 3-1 were combined.

While not explicitly claiming their assessment to be a sustainability assessment, (Raugei, Bargigli et al., 2005) combine tools such as LCA, MFA and EF supposedly within a multi-criteria assessment framework, to compare stationary fuel cells and natural gas turbines. In relation to Table 3-1, it is clear that all 3 tools above belong to the family of Physical Assessment Tools. In addition all criteria used were from the environmental dimension with no consideration of the economic or social dimensions. The assessment also exclusively focused only on the ‘upstream’ impacts of the life-cycle. This is not to say that such assessments should not be conducted or that there is no learning from such an exercise. The point here is that: (a) it is possible to use a variety of tools from the tool-space, perform ‘multi-criteria‘ analyses or ‘life-cycle’ analyses without necessarily conducting a sustainability assessment (b) and if, such arguably partial comparisons are
made between various options, then some caution (combined with some humility) may be necessary before making any recommendations for policy.

3.3 Development of the Sustainability Assessment Framework (SAF)

A number of different approaches to tool integration and selection were discussed in section 3.2.2 ranging from suggestions for a combination of specific tools, to the general suggestion of combining analytical methods within more flexible policy frameworks, to following an axiomatic approach for tool selection. The framework proposed here on the other hand is based on a classification of all tools into two groups or levels – framework level and analytical level. Framework level tools are those that have a high degree of flexibility (less precise) while analytical level tools are less flexible (more precise). This binary classification is notionally similar to the duality of sustainability assessment discussed earlier (Gibson, Hassan et al., 2005).

3.3.1 Framework Level Tools

Given the above duality, the role of the first level (framework level tools) is to capture the core or common ground across the multiple definitions and interpretations of sustainability (Murcott, 1997). Although this is a rather daunting task, the synthesis offered by the Sustainability-A Test suggests four common characteristics across a myriad of definitions (European Commission, 2006): (a) that sustainability is an inter-generational phenomena (b) that sustainable development is a process played out on several scales (c) that sustainability consists of multiple domains (at least three – economic, ecological and socio-cultural) and that the significance of the concept lies
precisely in the interrelations between them (d) that sustainability is characterized by multiple interpretations and that by nature it is complex, normative, subjective and ambiguous.

Thus framework level tools may be thought of as performing a number of functions (a) help define and characterize the problem by attempting to capture its complex, subjective and normative aspects by asking probing questions (b) provide the largest scope and flexibility for other tools to function within itself (tool nesting) (c) compensate for some of the knowledge gaps and methodological gaps (and perhaps also philosophical gaps) that may lie outside the boundaries of analytical tools and (d) guide the selection of analytical level tools for the assessment.

As a result, framework level tools should be capable of handling quantitative as well as qualitative information. They should also employ a certain level of creativity as they do not follow a specific algorithm but are able to capture some of the dynamics outside the 3 pillars of sustainability by accommodating and acknowledging gaps in our understanding, cross-cutting issues, multiple values, issues of scale, equity etc. Generally speaking, framework tools should have a philosophical undertone guided by fundamental questions relevant to policy-making, which would not only help define the problem but also contextualize the results of the assessment.

Although this is a tall order such multiple and broad requirements may be necessary for designing a complex and non-trivial assessment process such as sustainability
assessment. Given this tall order only a few tools qualify to fit the above description as we will see in the following sections.

### 3.3.1.1 The IA approach and the MCA process

Integrated Assessment can been described as a process that integrates knowledge from across different disciplines and stakeholders in order to understand complex issues and offer integrated insights to decision makers (Rotmans, J, 1998; Rotmans, J & Dowlatabadi, 1998). While IA models (IAMs discussed in more detail in section 3.3.2) are sophisticated analytical models, they are influenced by the less analytical IA approach and philosophy that underscores the importance of integration, public/stakeholder participation, understanding linkages and feedbacks, different scales and declaring explicitly assumptions, boundaries, uncertainties and limitations in the state of knowledge. Such an integrated and open approach enables for a move beyond isolated piece-meal approaches and sub-optimizations within the assessment process.

The SustainabilityA-Test consists of an entire family of Multi-Criteria Assessment (MCA) methods. Again a distinction is made here between specific MCA methods and

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45 Although IA and IAMs are related they are not equivalent. (Rothman and Robinson 1997) also point to this distinction between IA and IAMs and the tendency in the literature for it to become obscure. They also describe a set of 8 dimensions that define an idealized IA process/approach: (1) Location in the cycle (vertical integration) (2) Scope: sectoral, regional, and issue (horizontal integration) (3) Consideration of feedbacks and dynamics (4) Human adaptation to environmental change and policies to address this change (5) Recognizing multiple baselines (6) Quantitative/qualitative dimensions (7) Policy driven analysis (8) Involvement of stakeholders.
the underlying *MCA process*. The different stages of MCA according to (de Ridder, 2005) may be described as:

(i) **identify Policy Alternatives** (or Options), for comparison against each other

(ii) **select criteria** relevant to decision-making (sustainability pillars and beyond)

(iii) **assess** the **performance of each criterion** for each alternative (criteria score) and organize within an effects table (consequence table/impact matrix)

(iv) use a specific MCA ‘method’ (often a software package) to aggregate the information in the effects table and rank the options

(v) **apply sensitivity analysis** to examine robustness of ranks.

The stages 1-3 are not specific to any Multi-Criteria Assessment. However, step 4 entails the application of a specific approach/programme (i.e. NAIADE, PROMETHEE) to MCA which reflect the different schools of MCA\(^{46}\). The MCA stages which are common to all Multi-criteria assessments (stages 1-3) are collectively referred to here as the *MCA process*. Thus the MCA process goes beyond the application of a specific MCA algorithm or method and yet helps provide structure for framing the assessment. It also incorporates both quantitative and qualitative inputs from multiple criteria (across multiple domains) and identifies different options for assessment through stakeholder and public deliberation. These underlying characteristics of the MCA process which focus on systematically framing the problem to gain insights has been described by (de Ridder, 2005; Dias & Tsoukiàs, 2002; Roy, 1990) as being part of a constructive and creative approach.

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\(^{46}\) The different schools or methods of MCA are a result of different views of strong and weak sustainability and therefore different approaches to aggregation. See section 3.2 for more details.
An outcome of the IA approach is that it enables the practitioner to describe or frame the problem as clearly as possible taking into consideration the multiple streams of knowledge, both quantitative and qualitative, while questioning the validity of the information and methods used at arriving at what is ‘known’, and more importantly seeking and identifying gaps in the knowledge the absence of which may compromise the assessment – all this within a given spatial, temporal, technological, institutional and socio-economic context. The MCA process on the other hand can support the IA approach by enabling the acquisition of information necessary for the assessment through stakeholder and public input, provide structure to the thinking of stakeholders, and support multi-disciplinarity and transparency of the process (Polatidis, Haralambopoulos et al., 2003).

3.3.1.2 Scenario Analysis and Participatory Tools

Scenario analysis tools are able to represent all three pillars of sustainability as well as represent relationships and linkages of the scenario driving forces. They can handle multiple viewpoints, incorporate quantitative as well as qualitative information, consider timescales far into the future (representing interests of future generations), operate on any geographical scale and also include discussions of uncertainty, vulnerability and risk. Scenarios also work well in combination with many other tools. As such they may be considered as framework tools.

Stakeholder Analysis Tools also provide valuable input and contribute to the sustainability assessment process as they incorporate the values, knowledge and concerns
of the public and stakeholders in the decision making process. The IA approach described
above however encompasses stakeholder and public participation, and there have been
attempts to operationalize participatory processes within integrated assessments (Tansey,
Carmichael et al., 2002). Therefore, this tool family may be considered as being part of
the IA approach.

3.3.1.3 Minimum Conditions for designing Sustainability Assessments

Given their underlying philosophy and wide scope, in combination with their natural
synergy, the IA approach and the MCA process together satisfy many of the functions
expected of framework level tools (section 3.3.1) and fulfill the first part of the duality to
sustainability assessments. While scenario analysis tools as framework tools may
certainly be valuable, their utility for a given sustainability assessment process may
depend on the characteristics and demands of the particular problem being assessed. As
such scenario analysis tools may be incorporated with the IA approach and MCA process
as needed. Given the above, the IA approach and MCA process may be considered as
minimum conditions for designing sustainability assessment processes across a wide
variety of examples. Figure 3-1 in the next section discusses how the more analytical
level tools fit in within the framework level tools.

3.3.2 Analytical Level Tools

Given the broad requirements set-out in section 3.3.1 for framework level tools, most
other tools within the universe of tools may be classified as operating at the analytical
level, due to their greater analytical sophistication. Since SustainabilityA-Test consists of
over 50 assessment tools and methods (many of them shown in Table 3-1) across 7 tool
families, it is not possible (given the space) to go through each of them to demonstrate how they may be classified according to the two level (framework/analytical) hierarchy. Therefore, we will focus on the different tool families to demonstrate their classification, in section 3.3.2.1.

However, it may first be useful to use an illustration to suggest how the sustainability assessment framework (SAF) as proposed here may be visualized (see Figure 3-1). The outermost boundary (dotted lines) is the enclosure for the framework level, representing the first or lowest level of abstraction. The dotted lines represent the broad, flexible and somewhat amorphous nature of the framework level tools, while the two solid bi-directional arrows represent the synergistic relationship between the two framework level tools, reinforcing each others strengths and complementing their weaknesses. At the next level of abstraction, the large solid rectangles (vertical) represent the more precise analytical level tools (three are shown in Figure 3-1). While they perform specific functions, and provide input to the framework level tools, they may or may not interact directly with the other analytical level tools at the same level (hence the two dotted horizontal arrows between them). However, it is possible that each analytical tool may nest other analytical tools, methods or processes within it; these are represented by the smaller rectangles contained within each analytical tool. At this 3\textsuperscript{rd} level of abstraction (small horizontal rectangles) again these analytical tools methods may or may not interact with each other (hence the dotted vertical arrows).
How these analytical level tools are selected is one of the many challenges in conducting sustainability assessments. However, since sustainability assessment is arguably still in its embryonic stage without a sound theoretical basis, thus far most assessments that claimed to have conducted sustainability assessments were based on the practitioners selecting tools (or tool combinations) depending on their familiarity, comfort, availability or convenience with a given tool. Although often not made explicit, such reasoning is neither defensible nor valuable to the practice of sustainability assessment. It is hoped that this framework will contribute towards developing the necessary theoretical foundation for sustainability assessment.
3.3.2.1 Classification of Tools

Modelling Tools: A classic example of analytical tools is Modelling Tools. Although their analytical and computational sophistication is important to the analysis of complex problems, and their contribution undoubted, their output alone may be insufficient for sustainability assessment or for informing policy. Commenting on Integrated Assessment models (Parson & Fisher-Vanden, 1997) suggest that since “IA modeling, is not, and cannot be, all of assessment.”, they “can contribute best when embedded in broader assessment processes”. (Risbey, Kandlikar et al., 1996; Rothman & Robinson, 1997; Rotmans, J., Dowlatbadi et al., 1998) also discuss a range of limitations of IA models (IAMs) from representing mostly quantifiable parameters and links, to being considered as “truth machines” and consisting of needless model restrictions. Due to these intrinsic deficiencies the family of Modelling tools (Table 3-1), which include the traditional disciplinary models as well as the IA models (IAMs), may be classified as analytical level tools.

Physical Assessment Tools (PAT) and Monetary Assessment Tools (MAT): As with modelling tools it is not difficult to accept that the above tools would classify as analytical level tools as each of them performs specific analytic functions and calculations. For instance PATs such as MFA, LCA, and EF perform calculations on flows of energy, material, emissions or land usage. Similarly MATs such as CBA, CEA or Green Accounting Tools deal with calculations of costs and benefits often aggregated and specified in monetary units or in combination with physical units, within their respective frameworks.
**MCA Methods:** As discussed in section 3.3.1.1 MCA methods may be carried out in 5 sequential stages, the last two of which are purely analytical. In stage 4 the method for the ranking of the alternatives may depend on one’s viewpoint and degree of polarization towards strong or weak sustainability. For instance, while those that allow compensation reflect the weak sustainability approach (compensation for the poor performance of one criterion by the better performance of another), those that don’t allow any compensation belong to the strong sustainability approach, and those that allow partial compensation are in between. As such the performance of the criteria may be aggregated either based on (a) compensatory methods (b) partial compensatory methods or (c) non-compensatory methods – each likely to produce different rankings of the alternatives. (This distinction largely separates the 7 different MCA methods considered in the SustainabilityA-Test (de Ridder, 2005; Munda, 2005)). The last stage in any MCA method is also largely analytical as it consists of sensitivity analysis.

**Sustainability Appraisal Tools:** Although the SustainabilityA-Test (see Table 3-1) describes, Strategic Environmental Assessment (SEA), Sustainability Impact Assessment (SIA), Vulnerability Assessment (VA) and Indicators for Sustainable Development (SD) as ‘framework tools’, most of these tools fall somewhat short in meeting the criteria for framework level tools (section 3.3.1) adopted here. For instance, SEA has an environmental bias to the assessment although it may occasionally include other dimensions of sustainability. According to the SustainabilityA-Test issues such as cumulative impacts and long-term effects are also not considered within SEA.
Commenting on a variety of applications of SEA in Canada and globally, (Noble, 2002) suggests that one weakness of SEA are a lack of a structured framework and points to the importance of a “systematic assessment framework....within which a variety of methods and techniques can be applied”, to guide decision making across all sectors. This is precisely what this paper intends to achieve in the SAF proposed here. Like SEA, VA also shares some features of framework level tools (section 3.3.1), but its main goal of assessing vulnerability (or risk) may be included within the Integrated Assessment approach, discussed above. As such it may be considered a sub-set of the IA approach.

A major limitation of Indicators for SD is that indicator sets tend to contain almost exclusively quantitative data – this largely disregards the qualitative aspects of sustainability. Secondly, it suffers from the *availability bias* – meaning that even for quantitative data, if it is not available, it will not be measured/reported. Thirdly, a parameter which is measured as an indicator often can have a very weak correlation with the actual impact that is policy relevant. Finally, aggregation of indicators (whichever happen to be available, in whatever units) non-reflexively, in an attempt to condense and reduce large data sets, is also potentially undesirable (Farrell, A. & Hart, 1998; Funtowicz, S. O. & Ravetz, 1994; Giampietro, Mario, Mayumi et al., 2006; Munda, 1996, 2005). In an attempt to improve on some of these weaknesses, a recent study argues and demonstrates the importance of making indicator systems more dynamic, integrated and participatory (Carmichael, Talwar et al., 2005). Nevertheless, although valuable and ubiquitous, Sustainability Indicator systems as presently used may be most suitably classified as an analytical level tool.
In the next two sections we will discuss some of the conceptual challenges for Sustainability Assessment and how they may relate to the two-level (framework level/analytical level) Sustainability Assessment Framework proposed here.

3.4 Conceptual Challenges for Sustainability Assessment

There are a number of key conceptual challenges that underlie the Sustainability Assessment process. However, not all of the challenges discussed below may be present at all times most will need to be addressed in the context of a stakeholder engagement process. While there may not be a unique response to each challenge, it is expected that within the participatory public/stakeholder process, depending on the context of the particular problem being assessed, an agreement would be reached as to the appropriate response. The key however, is to be aware of these challenges in sustainability assessments.

**Complexity:** Complexity is an inherent feature of most sustainability assessments, by virtue of the complex systems likely being analyzed as well as the multiplicity of societal values regarding what encompasses the notion of sustainability. As a result of the systems complexity often we run into the fallacy of ‘ceteris paribus’, where it is assumed that given a certain known condition of the system ‘all else is equal’ or that all other parts of the problem scale accordingly. Since complex systems are rarely homogeneous or linear, as a result of this assumption often one may fail to incorporate important dynamics and relevant aspects of the problem.
**Problem Framing:** How the problem is framed is also a crucial part of the sustainability assessment process. Alternative problem framings of a given problem may result from ‘ceteris paribus’ type assumptions, or from the different societal values represented in the stakeholder group. While the former could result in a systemic error in the assessment, the latter challenges the moderator or practitioner to find a common framing that the stakeholders may agree upon. However, this still leaves the possibility of contested framings by a different public/stakeholder group. If the stakeholder group is representative of the population with stakes in the problem being assessed, then the discrepancies are likely to be small. If public/stakeholder representation is biased or skewed then unless the same bias is present in the selection of the other stakeholder group, one will run into different problem framings. Both these issues are problematic and therefore (a) care must be taken in the selection of public/stakeholders for the participatory process and (b) all the values and judgements that go into the framing of the problem must be accurately documented, in order to trace the origins of the problem framing, if necessary.

How the problem is framed will also determine the criteria that get incorporated into the assessment, through the participatory process. The set of criteria chosen will have a significant effect on the entire assessment and therefore the problem framing presents a critical challenge.

**Incommensurability:** Given the multi-faceted and multi-dimensional nature of sustainability, each and every measurable parameter or impact criteria will be measured
in units that are likely to be incommensurable with some of the other parameters. Furthermore, not all aspects and values embedded within the notion of sustainability are easily measurable or quantifiable, further complicating the issue of commensurability. However, different groups are likely to see different degrees of commensurability (Funtowicz, S., Martinez-Alier et al., 1999) – strong or weak commensurability – and there can be polarized views on this even within a given participatory process. Again the challenge lies in finding the appropriate degree of commensurability that can be agreed upon. What is important to remember however, is that the conclusions drawn from the assessment may depend on how the issue of commensurability was treated.

**Uncertainty:**Uncertainty is a phenomenon that pervades most complex technical and socio-technical systems. It is also an inherent feature of the future. It may rise from the unpredictability of future conditions and our actions, complex relationships of the system which models or assessments failed to capture, varying definitions, varying boundary conditions and problem framings, or poor or non-representative data used in a particular model or assessment (Manning, 2006).

Although uncertainty is prevalent across most disciplines, how it is reported and communicated differs greatly. Given the multi-disciplinarity of sustainability this poses a particular problem for sustainability assessments. As such, a common framework would need to be adopted for a given assessment process itself\(^{47}\). The point however, is that since uncertainty (due to all the above reasons), is likely to contribute to the overall uncertainty of the assessment its explicit treatment (either quantitatively or in a

\(^{47}\)The challenges of developing such a framework for the IPCC Fourth Assessment report has been reported by (Manning, 2006).
qualitative manner) should be an important feature of sustainability assessments. Also, it would be important to explore more carefully areas of the problem domain whose uncertainty is likely to cause the greatest concerns for any conclusions from the sustainability assessment.

**Limited Knowledge:** Another major challenge for sustainability assessments is the limited knowledge or gaps in our knowledge about certain parts of the problem domain. Often when assessments are driven by the goal of computing a final score or ranking, areas of limited or no knowledge get left out. However, for sustainability assessments this may not be acceptable, as the goal is to improve our understanding of the system so that we may drive it along more sustainable trajectories. While it is not possible to quantify the unknown, not even acknowledging how those gaps may relate to what is known may (a) prevent the actual inclusion of that information in the future when more is known (b) give a false sense of confidence to the results of the assessment and (c) will significantly reduce our chances of affecting change toward a more sustainable system.

**Equity:** The Brundtland Commission’s definition of sustainable development makes clear the importance of inter-generational equity (Brundtland, 1987) – which is based on equity over time. Similarly it is important to consider equity across space – intra-generational equity. The common challenge is that there is no common metric or method for measuring equity. However, equity may be viewed in terms of the population or group receiving benefits or impacts of a certain action. For instance, since GHG emissions and their climate change impacts are felt over longer time-frames (and also
across larger geographical regions) than local air-pollution impacts, identification of the groups affected would be a first step in the incorporation of equity into the assessment. While different stakeholder groups and members within a group would value equity issues differently, and given that equity issues are likely to manifest themselves differently in different assessments, incorporating inter/intra-generational equity within the assessment would likely be a challenge for the sustainability practitioner. However, given the importance of inter/intra-generational equity to sustainability, ignoring it completely from the assessment may not be desirable for sustainability assessments.

Scale: Issues of scale also pose challenges for sustainability assessments in different ways. At one level issues about inter-generational and intra-generational equity may be seen as occurring at different scales (temporal and spatial scales respectively). At another level, the length of time-scale or size of geographical region may be the bounding conditions for any given study. Since sustainability assessment are likely to incorporate results from a multitude of studies, it is important to consider if the results are strongly tied to the underlying scale of analysis. At yet another level scale may be about the different units of measurement and their integration – this we discussed above under challenge of incommensurability.

Also different time-scales may be associated with different processes. For instance, impacts of ozone on human health take place on the order of hours/days after being emitted, while GHGs can stay in the upper atmosphere for a few centuries and can cause impacts long after they have been emitted. Using hierarchy theory to analyze the concept of sustainable development (Giampietro, Mario, 1994) discusses how the chosen
scale of analysis can cause a discrepancy in the values and perspective even when assessing the same phenomena or action. Thus, if results from other studies are to be incorporated into a sustainability assessment, it is important to consider the impact of their underlying scales, prior to their inclusion into the assessment.

3.5 Two Levels of SAF and Conceptual Challenges for Sustainability Assessment

Given the large differences between the framework level and analytical levels discussed earlier, the conceptual challenges for sustainability assessment have different implications for these two levels of the Sustainability Assessment Framework (SAF). As we will see, while most of these challenges would need to be dealt with at both levels, some would need to be addressed more crucially at the framework level.

The complexity that arises from the plurality of societal values will manifest itself in many aspects of the sustainability assessment. It will be most obvious during the public and stakeholder engagement process and will influence the discussions about problem framing and criteria selection. The tools designed to deal with these issues are the ‘IA approach’ and the ‘MCA process’. Mapping the system complexity of the problem under assessment is also a component of the IA approach. As such these are all challenges that are more suitably dealt with at the framework level.

The problem of ‘ceteris paribus’ is usually a result of undermining system complexity. If the integrated assessment of the problem identifies and maps the relevant parts of the
problem and the associated dynamics, then it is less likely to commit this fallacy. Hence system level analysis cannot be left to the analytical level, as the analytical level tools, despite their analytical sophistication, are generally incapable of addressing system wide dynamics.

Incommensurability is also an issue that needs to be addressed at the framework level. While the performance characterization of individual criteria occurs at the analytical level with specific analytical tools, for their integration and assessment they will need to be brought back down to the framework level. Here the MCA process will be instrumental. At this point, through the participatory process and ensuing discussion between public, stakeholders and experts a collective level of commensurability (weak/strong) will need to be agreed upon; depending on the outcome of this discussion it may be necessary to go back to the analytical level and utilize a specific MCA method (see Table 3-1) as appropriate.

Uncertainty will need to be dealt with at both levels. While each chosen analytical level tool will need to provide a treatment of uncertainty for the relevant criteria (either qualitatively or quantitatively) it will need to be communicated back to the framework level. The challenge for the team of sustainability practitioners would then be to holistically analyze the uncertainties across the problem domain. This will provide a greater understanding of the problem and their relative contributions to the system wide uncertainty. Where the greatest uncertainties lie, will directly affect any conclusions on sustainability that may or may not be reached.
The integrated assessment approach stresses the importance of not ignoring areas of limited knowledge (Morgan, G. & Dowlatabadi, 1996). Again, this is a challenge which is difficult to deal with at the analytical level as analytical tools are designed to perform very specific tasks with specific outputs. Therefore, a close examination of areas with limited information of the problem being assessed, and their acknowledgement at the very least, would need to be conducted at the framework level. This is likely to be a collective effort by the sustainability practitioners.

Issues of scale also have important implications to the two levels. Assuming that the incorporation of inter/intra-generational equity is important for sustainability assessments, first it needs to be decided at the framework level (through the participatory integrated assessment) the boundary conditions for these two criteria (i.e. how far into the future and how large a geographical region to consider) relevant to the assessment. Also, since there is no precise recipe for their measurement, the exact mechanism of measuring it, in relation to the problem, needs to be addressed. Neither of these can be left to be determined at the analytical level, as these considerations are beyond their scope.

Other scales relevant to the sub-assessments would depend entirely on the problem being considered and how it has been framed. Different processes have different characteristic time-scales or geographic regions of influence. Hence, limiting oneself to temporal and geographical scales that do not capture the particular process or effect may only provide incomplete or perhaps inaccurate conclusions. Furthermore, if different timescales and
spatial scales are used for the different sub-assessments (with the aid of different analytical level tools) when their results are communicated to the framework level, care must be taken to ensure that the integration of the data from the different underlying spatial and temporal scales do not present any conflict or inconsistency in the overall assessment. Given the wider scope of these concerns, they too would need to be considered at the framework level.

A related issue to scale is that of resolution. Even if the appropriate scales have been chosen, it is important to determine the appropriate resolution for any given particular sub-assessment. This is an issue that can be determined at the analytical level.

As we have seen above, most of the conceptual challenges need to be dealt with at the framework level as they are fairly broad in scope and beyond the scope of most analytical level tools. Also, in the above discussion it became evident that the application of the framework tools is fairly intensive and require deliberation within a participatory process. Furthermore, that the sustainability assessment involves interaction between the framework and analytical levels in an iterative manner.

3.6 Selection of Analytical Level Tools for a Transportation example – Light Duty Vehicles

In this section a preliminary application of integrated assessment within a multiple criteria (both quantitative and qualitative) process will be applied to an example from the transportation sector (light-duty vehicles). Although ideally the application of the framework tools would be conducted with a team of experts within a public and
stakeholder engagement process, the discussion here will serve as an illustration of how even a preliminary and partial application of the framework level tools can help with the selection of the appropriate analytical level tools for the analysis. It will also demonstrate that the selection of analytical level tools will be a result of a systematic and transparent process that emerges from the unique properties of the problem itself, and not by any arbitrary process of convenience, availability or familiarity.

Below, the discussion is driven along a variety of sustainability criteria in the technical, environmental, economic and social dimensions (as well as combinations of the above). It attempts to simulate the criteria that may emerge from a participatory integrated assessment, framed within a multi-criteria process. The list of criteria is by no means complete. However, it is hoped that collectively they represent important elements of the problem domain that are likely to emerge through a participatory process. Table 3-2 below provides a list of the dozen chosen criteria, the sustainability dimensions they emerge from and their relevance to the conceptual challenges discussed earlier.

The process is lengthy but necessary, as the goal is to develop an integrated understanding of the problem, the outcome from which would emerge the recommendations for the necessary analytical level tools in order to conduct the actual sustainability assessment. As we will see, much can be learned from this preliminary process alone.
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<td>Environmental</td>
<td>Systems Complexity</td>
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**Table 3-2: Criteria, dimensions and relevance to conceptual challenges**

**Vehicle Manufacture and Toxic Release:** Figure 3-2 shows the various components relevant to the assessment of an automobile. The fuel-chain\(^{48}\) component is the sum of the feedstock recovery, fuel production, and the use of that fuel over the operating lifetime of the vehicle. Focusing on fuel chain emissions only (often called well-to-wheel emissions) (Linssen, Grube et al., 2003; Pembina, 2002; Wang, Zhou et al., 2005) would ignore any economic, social and environmental impacts from the vehicle chain. The

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\(^{48}\) The fuel-chain is often referred to as fuel-cycle. Since cycle implies a closed loop it may be more appropriately called a fuel-chain instead, due to the series of linked (hence chained) events.
vehicle chain component includes the material production, manufacture of vehicle and motor (internal combustion engine (ICE), fuel-cell or battery) as well as the disposal and recycling of the vehicle. The energy and environmental emissions (gaseous and toxic) from the vehicle disposal and recycling are arguably small (Maclean, Heather L. & Lave, 1998), but the energy and toxic emissions from the vehicle and motor manufacture phase of the vehicle chain may not be ignored if ICE vehicles are being compared against Fuel Cell Vehicles (FCVs). Most assessments ignore the vehicle manufacture stage and its impacts (Brinkman, Wang et al., 2005; Contadini & Moore, 2003; Huang & Zhang, 2006) based on the fact that the energy consumption from this stage only account to about 10% of life-cycle energy consumption for vehicles. The fallacy here is due to a 'ceteris paribus' (all else is equal) type assumption. However, if one considers the life-cycle toxic releases of a vehicle, almost 60% of the toxic materials released are from the vehicle manufacture stage (Maclean and Lave 1998). Since human health impacts are closely correlated to toxic releases rather than energy consumption, studies or assessments that ignore the vehicle manufacture stage due to the ‘10% rule’, are implicitly valuing ‘energy consumption’ of the vehicle operation phase over the potential direct and indirect human health impacts from vehicle manufacture.

49 The vehicle-chain is often referred to as vehicle-cycle.
Energy, Energy Efficiency and Vehicle Manufacture: The omission of the vehicle manufacture component of the vehicle-chain may even be justified, if the material and energy requirements for vehicle manufacture of all the vehicle options compared were almost identical. However, when comparing hydrogen and fuel cell technologies not only is the fuel chain very different (see Figure 3-3), but the material and energy requirements for the production of the automotive fuel-cell (PEMFC - Polymer Electrolyte Membrane Fuel Cell\textsuperscript{50}) are clearly different from ICES (Pehnt, 2001). Another key feature of the PEMFC, which differentiates it from ICES, is its much higher operating or thermodynamic efficiency - PEMFC are on average 2.5X more efficient (International Energy Agency 2005). As a result of this efficiency a PEMFC would consume about 25%-50% less energy\textsuperscript{51} on a well-to-wheel (fuel-chain) basis (CONCAWE, 2004; Weiss, 2001).

\textsuperscript{50} This is the type of fuel cell that is being considered for automotive applications.

\textsuperscript{51} Even including the potentially higher energy consumption for hydrogen production.
Heywood et al., 2003). Based on this information the share of energy consumed in the vehicle manufacture (vehicle-chain) is no longer only 10% of life cycle energy consumption, but a larger share of the total life cycle energy and there is therefore even less reason to ignore this stage. These special characteristics of the hydrogen fuel chains combined with those of the fuel cells make it necessary for any sustainability assessment to include the impacts of the fuel chain as well as the vehicle chain.

Depending on the motivation of the assessment, if the goal was merely to compare across different vehicle technologies (horizontal analysis) then areas where impacts are the same, could be omitted from the analysis (if so desired) without affecting the overall assessment. However, if the goal is more of an impact assessment then all impacts would be deemed important (including those that occur vertically within a particular alternative).
Aggregation of Well-To-Wheel Emissions: Another special characteristic of hydrogen and fuel cell based systems is that there are virtually no tail-pipe emissions. The health impacts in dense urban areas from automobiles due to formation of photo-chemical smog as well as particulate matter are well documented (Committee on Air Quality Management in the United States, 2004; Vedal, Brauer et al., 2003; Ware, 2000). Downstream or tail-pipe emissions (TTW – tank to wheel) in contrast to upstream emissions (WTT – well to tank) are highly decentralized (multiple tail-pipes) and therefore almost impossible to capture. As such technologies that have low or near-zero emissions at the tail-pipe would contribute significantly less toward the negative urban
health impacts from emissions. The non-equivalency of the WTT and TTW impacts imply that the addition of the WTT emissions to the TTW emissions to arrive at an aggregate value for well-to-wheel (WTW) emissions should be avoided, unless it is used within the assessment with the above understanding. Quite often assessments of ICE and FCV technologies seem to ignore this important fact and thus introduce a systemic error into the assessment.

The discussion above about the importance of including the fuel-chain as well as the vehicle chain into the sustainability assessment, and the non-equivalency of the WTT and TTW impacts, emerges from an attempt to improve the framing of the problem. It has been noted elsewhere, with respect to the differences in the physical and chemical properties of hydrogen, that the impact of these unique properties need to be fully considered in order to develop an appropriate assessment (Ricci, Newsholme et al., 2007). Similarly, as the performance and manufacture of fuel cell systems also differ greatly from incumbent technologies, one must be careful with ‘ceteris paribus’ type assumptions in the sustainability assessment process.

**Air-Pollution impacts:** The emission of air-pollutants such as oxides of sulphur (SOx), oxides of nitrogen (NOx), volatile organic compounds (VOC) and particulate matter (PM) from transportation are easily measurable. The significance of these measurements has to do with their adverse effect on health. However there is considerable uncertainty and gaps in the knowledge of air-pollution science and in the measurement of impacts of air-pollutants. Although at present statistically significant associations exist between
some air pollutants and observed human health effects, due to the lack of specificity they cannot be understood independently from risk factors with the same outcomes (National Research Council, 2002). This may be partially attributed to the interactions between co-pollutants and their resulting confounding effects.

Studies of PM, perhaps the most widely discussed transport related air-pollutant, have shown that ambient concentrations are not only affected by traffic flows, but also by local building and geometry of the streets, resulting in ‘street canyon’ effects (UK Department for Transportation, 2006). Therefore, standard dispersion models may be unable to completely account for local conditions and may result in questionable conclusions. In assessing the toxicological effect of PM, present studies make the assumption of equal toxicity for all the particle components that constitute PM. Although this may be due to information being inadequate for determining the relative toxicity of different particle types, according to (National Research Council, 2002) the assumption of equal toxicity may be inappropriate and therefore studies need to move towards measurements of differential toxicity. Another potential problem with PM measurements today may have to do with the emphasis on the measurement of mass. Recent research has consistently shown the significance of the fine fraction (PM2.5) and particularly the ultra fine particles (UFP- less than 0.1 microns) on health effects. The UFP fraction makes a negligible contribution to the mass of PM10 (inhalable fraction) but in terms of the ‘number of particles’ or ‘surface area per unit mass’, their contribution is significant. Studies have shown that peak deposition of particles in the alveolar region of the lungs occurs for particles with diameters between 0.01 and 0.1 microns (Biswas & Wu, 2005;
Oberdorster, 2000). Smaller particles are also likely to enter the bloodstream, thereby directly affecting the cardiovascular system (Nemmar, Hoet et al., 2002). The larger relative surface areas result in a higher amount of adsorbed potentially toxic species, while greater penetration results in a higher effective dose. The point here is not that inhalation of PM does not affect health, but on the contrary that we may be underestimating the impacts due to a poor understanding of the science and hence metrics used. The significance of PM emissions again is due to the large difference in this performance measure across the technology options in Figure 3-3.

As far as ground level ozone (GLO3) is concerned, its formation from precursors such as NOx, VOC and sunlight, and its health effects are also not well understood. According to (European Environment Agency, 2006) although emissions of ozone precursors have declined by about 30% in the EU this has not resulted in comparable declines in average ozone concentrations, especially in city centres. This point to the complex processes underlying ozone formation as well as sunlight and climatic conditions. For instance, the highest concentrations of ozone are not always found in city centres, where ozone precursors are usually emitted, because an abundance of nitrogen oxide from traffic often suppresses ozone formation. Since ozone can be transported by the wind for distances of 400-500 km a day, its health (and environmental) impacts are often felt in suburban and rural areas far from the source of the pollutants. Again due to intra-generational concerns of sustainability, even though these effects are presently not accurately measurable, it may be important to consider at least qualitatively within the assessment.
According to (Vedal, Brauer et al., 2003) data suggesting that there does not appear to be a lower threshold concentration for air-pollution below which adverse effects cannot be detected “…raises concerns that associations are not reflecting the effects of measured pollutants but rather some factor or combination of factors, such as, for example, unmeasured air pollutants or uncontrolled features of meteorology that are correlated with the measured pollutants.” The above discussion on air pollution and the lack of understanding in its causal effects make it challenging, to say the least, to assess health impacts from air pollutant emissions of the petroleum based technology pathways discussed here. When problems are characterized with high levels of uncertainty as well as variability as in the case of air-pollution and its impacts, the remaining option may be to ask experts for their best professional judgement (Morgan, G. M., Kandlikar et al., 1999). Such methods are gaining popularity in fields such as climate change and health risk assessment (National Research Council, 2002).

The last few points illustrate the incomplete state of knowledge on air-pollution. In the process we learned how the gaps and limitations in our knowledge can have serious implications for the sustainability assessment.

**Intra-generational Impacts:** In addition to ensuring that relevant components of the problem are captured and incorporating criteria that may be locally relevant, a multi-criteria sustainability assessment should also include consideration for intra-generational impacts – impacts that are geographically distributed often outside the immediate problem boundary. For instance, while using total CO₂ emissions may be a reasonable
proxy to its contribution to the impact on global warming, using total solid waste, measured by its weight, may be a poor indicator of its actual environmental or social impact. The PEM fuel cell production process is very materially and energy intensive (Mehta & Cooper, 2003; Pehnt, 2001), involving a variety of different materials (such as graphite, platinum etc.,) that are mined in different parts of the world with varying degrees of environmental impact and societal risk. If intra-generational impacts are deemed important and if they are different across the technologies (or alternatives) considered, the composition of the solid waste, their geographical distribution as well as their relative risks may be important to consider.

**Quality of Life (Noise):** Fuel-cells produce energy through an electrochemical process and as such there are no moving mechanical components that generate noise. Although we have socially accepted the noise generated from ICEs, the quality of life (due to noise levels) for those living in urban areas, near major traffic routes or even near fuelling stations might be seriously affected due to sleep disturbance and potential impacts on cognitive development in children (UK Department for Transportation, 2004). Therefore, the much lower noise levels from FCVs and EVs (electric vehicles) might be an important criterion for some. Since the level of noise is practically the same from all ICE vehicles (of a given class) presently there is little need to measure the difference in noise between vehicles. However, given the substantial difference in this performance measure between ICEVs and FCVs (or EVs), sustainability assessments of these technologies would likely need to value this benefit to society. Little work has gone into this area, but given the large increases expected (in absolute and relative terms) in urban population
over the coming decades, further research in this area might be an important consideration. Incidentally both FCVs as well as EVs have near-zero or zero emissions at the tail-pipe and low to no noise generated from its motor, while ICEs have emissions as well as noise. Given this incidental relationship between emissions and noise, the valuation of these performance criteria could be combined to improve the design and effectiveness of the valuation method employed. Non-market valuation methods/techniques such as ‘contingent valuation’ may be employed here to measure the societal benefit/cost of these criteria.

**Fuel Safety:** Hydrogen was blamed for more than half a century as being responsible for the notorious and widely publicized explosion of the *Hindenburg*. This myth was finally put to rest in 1997 by a NASA engineer (Bain, 1997, 1999), but the public conscience may still be affected by the legacy of the Hindenburg and its association with hydrogen. However, the sustainability of hydrogen as a fuel should not be evaluated based on decades of misinformation but on its unique properties that make it safe or less safe as a fuel. All fuels can be dangerous if not handled, stored and transported with respect to their particular characteristics. Fuels may be characterized based on their physical and chemical properties such as flammability limits, ignition energy, diffusion co-efficient, specific heat, explosion energy, flame emissivity, ignition temperature and flame temperature. These physical and chemical characteristics of hydrogen are quite different

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53 When particular goods or impact of a policy (less noise) is hard to measure directly as it is not traded in regular markets, economists have developed techniques such as ‘contingent valuation’ to conduct surveys that measure public’s willingness to pay (WTP), in order to arrive at a value for the public good.
from traditional fuels such as gasoline, diesel or methane. In fact, in 5 out of the 8 fuel characteristics mentioned above hydrogen has a superior performance and roughly the same for another (National Renewable Energy Laboratories, Hydrogen Research Institute et al., 1998; Veziroglu, 2001). In addition, hydrogen and its combustion products are also non-toxic and non-corrosive compared to other fuels. The fuelling of hydrogen (or the charging of an EV) will also not emit harmful volatile organic compounds (VOC) that pose a direct risk to health when inhaled.

While there has been some work on the discussion and risk assessment of hydrogen as a fuel (Cadwallader & Herring, 1999; NASA, 1997; Ricci, Newsholme et al., 2007), it is imperative that they feature more prominently in the risk communication to the stakeholders. The resulting risk assessment would no doubt be another valuable input into the social dimension of the sustainability assessment of the various vehicle technologies.

The above two points about quality of life and safety are important considerations for society which may be necessary to include within a MCA process. Given that the public may not be aware of the particular characteristics of these new technologies and fuels, it is the responsibility of the sustainability practitioner to inform the public and stakeholders of these differences in performance measures when attempting to develop an impact matrix. Furthermore there may be other concerns that the public may want the practitioner to include, which may have gone unnoticed to the generally scientific and quantitative approaches of experts. While health and social impacts are important public concerns, the economic implications are also of great concern to the public. The next few
points discuss issues of energy security and technology and fuel costs as well as tools and methods that may be needed for their assessment.

**Energy Security:** Issues of energy-security or geo-political risk of primary energy (Jaccard, Mark, 2005), may also be another socio-economic concern for society. The global distribution of the various fossil primary energy sources is heterogeneous. While the geo-political risks associated with conventional crude-oil are clear due to their vast concentrations in politically unstable regions, other fossil energy sources such as coal and natural gas are more evenly distributed. Therefore continued reliance on petroleum and petroleum based transportation for regions and nations with dwindling or no petroleum resources may in the long-term prove to be detrimental socially as well as economically. Given these differences in geo-political risk, technological pathways in Figure 3-3 that do not rely on petroleum based fuels are likely to experience less geo-political risk. Therefore, geo-political risk may also be an important criterion to consider either quantitatively or qualitatively in the sustainability assessment.

**Fuel Cell Cost:** In the economic dimension the cost of the fuel cell is clearly an important issue. However, PEMFC are not yet produced commercially for automotive applications and so the pre-commercial cost of a FCV produced today for demonstrations and other pre-commercial applications are approximately 30 to 40 fold greater than their ICE counterparts. Using this higher cost for the FCV (which is not based on volume manufacture) provides an unfair advantage to other vehicle technologies in Figure 3-3. The literature on technology diffusion has clearly shown the cumulative effects of
technological learning (Argote & Epple, 1990; Arrow, 1962; McDonald & Schrattenholzer, 2001) where ‘experience curves’ demonstrate the productivity gains over time due to ‘learning by doing’ and ‘learning by using’ phenomena. Therefore, when comparing against other technologies the cost-performance for FCV needs to be adjusted to a value (or range) that would reflect the commercial costs of volume manufacture. Given that there is little to no information available publicly on the exact components and their costs (for propriety reasons) of current PEMFC, such an estimate would have to be made based on a number of assumptions of the technology as well as society’s willingness to pay for a zero emission (at tail-pipe) vehicle.

**Hydrogen Fuel Cost:** A similar problem occurs in trying to estimate fuel costs for FCVs. As seen in Figure 3-3, there are at least 3 different technologies of producing hydrogen from a secondary energy carrier. The costs of the primary energy source as well as the costs of producing the secondary energy carriers are well known today, but the costs of hydrogen production depend on the volume produced. A further uncertainty lies in the configuration of the hydrogen infrastructure - whether it will be based on centralized production (from coal gasification or natural gas reforming) and then distributed through pipelines or produced locally at fuelling stations in a decentralized configuration (from natural gas reforming or water electrolysis) (Ogden, 1999b; Roberts, 2003). The centralized configuration which can potentially produce hydrogen at a lower cost due to larger volumes has the additional costs of the pipeline infrastructure, whereas the decentralized configuration may have higher production costs due to lower volume and relatively higher plant costs. Finally in a carbon constrained world, costs of carbon
sequestration (or carbon capture and storage) will certainly need to be considered, not to mention the societal risks from leakage of sequestered CO₂. The costs of all these components to the final cost of hydrogen production and delivery are highly uncertain therefore the economic dimension of this problem is very poorly understood. If time and resources permit, a scenarios analysis of different hydrogen production processes and infrastructure configurations which are relevant to the region may be conducted to estimate the ranges for delivered fuel costs. Within this sub-assessment CBA may be incorporated within these scenarios to assess total costs with appropriate discount rates used for capital expenditures.

A number of criteria as well as tools necessary to incorporate social and economic concerns were discussed above. While local air-pollutants may affect human health directly, impacts from upstream emissions of fossil fuels as well as spillage during their transport need to be considered due the inclusion of non-petroleum based technologies and fuel options considered within this assessment (Figure 3-3).

**Carbon Footprint:** Due to the gradual disappearance of easily accessible petroleum resources it is important to note that the carbon as well as energy footprint of petroleum based fuels is gradually increasing. Put it differently, as conventional oil reserves start depleting, the drilling activity as well as the energy input to extract the marginal barrel of oil from the existing resource-base continues to rise. The increased energy input and capital spending would be reflected in the final cost of a barrel of oil, but the increased carbon footprint does not, in a global economy unconstrained by carbon. The share of
non-conventional oil such as oil-sands, ultra-heavy oil or oil-shale has already increased in the global petroleum mix and this trend is likely to continue. The production of unconventional oil further increases the carbon footprint of the petroleum fuel mix. Therefore any measurement of the environmental impact of fuels within the sustainability assessment should reflect this new reality and not be based on past data. (Holden & Hoyer, 2005) have developed a system to measure the ecological footprint of fuels. Although this is a good start, it only measures the land area needed for energy production and sequestration and does not incorporate the increasing energy and carbon footprint of modern and future petroleum production. The exclusion of this fact from the analysis is likely to give petroleum based ICE technologies their deserved credit for improving carbon emissions at the tail-pipe, without the penalty of increased upstream emissions from feedstock extraction.

**Oil Spills and Bio-diversity:** CO₂ emissions (as well as other gaseous emissions) are common indicators of environmental pollution. Often the impact of oil spills from marine petroleum transportation on marine eco-systems and bio-diversity go unnoticed (EEA, 2003). Again, given that the fuel cell based technologies are linked to non-petroleum based energy sources, the above impact is non-uniform across the technological pathways shown in Figure 3-3. Therefore, depending on whether a given jurisdiction imports oil through shipping routes the inclusion of this environmental criterion may be relevant to the sustainability assessment.
Although the process above was somewhat lengthy, the preliminary application of an integrated approach to the assessment of the problem domain while being open to multiple criteria (both quantitative and qualitative) helped discover some of the tools and methods that may be required for the sustainability assessment. In addition, we were able to analyze some of the special characteristics of the light-duty vehicles and their impacts, through that process. It should be noted however, that the order in which we proceeded here, by first starting with alternatives and then searching for relevant objectives and criteria may not be characteristic of other situations. The highly technical nature of the alternatives (see Figure 3-3) enabled us to identify them without prior stakeholder deliberation. In general the reverse is recommended in the multi-attribute decision analysis literature, whereby first focusing on attributes and objectives (resulting in indicators/criteria) in a multi-attribute stakeholder process may lead to developing alternatives that better achieve the objectives (Keeney & McDaniels, 1999; Keeney & Raiffa, 1993).

The various themes discussed above were either within the environmental, economic, or social dimensions, or within their cross-cutting combinations. Although in principle it is important to be balanced across the different dimensions (Munda, 2005), some areas may have received more emphasis than others – this is also likely to happen when stakeholders are involved. Two reasons maybe offered for this: first, criteria that are almost identical across the various alternatives (i.e. costs for developing road infrastructure, gender bias, social inclusion/exclusion) were not included as they did not help differentiate between the alternatives, and secondly for some criteria, information
was simply not available (i.e. change in employment for fuel cell manufacture compared to ICE).

Although specific data may not be available, it is important to make note of the value or significance assigned to the particular criteria by those who help frame and define the problem context. The identification of these values (even when data gaps exist), is important for the sustainability assessment, so that they may be included when they become available. Thus the sustainability assessment becomes a dynamic learning experience not only about new information, but also about how the values and preferences change over time.

As noted earlier the discussion above is a result of a partial application of the framework level tools (IA approach and MCA process). A more complete application would be conducted within a stakeholder and public participatory process. While this process would likely include a team of experts representing the areas of expertise that emerged from the above preliminary analysis, the selection of the appropriate ‘non-expert stakeholders’ for the analysis is not as straightforward. The reason for this is because it is conceivable that there may be non-equivalent groups, and different sets of representatives for a given group. While the stakeholder engagement process was not within the scope of this study, careful attention needs to be paid to this process as the sustainability assessment as well as any conclusions, choices and decisions made will be influenced not only by how the problem is framed and tools used for the assessment, but also by the design of the stakeholder engagement process.
3.6.1 Results: Recommendations for Analytical Level Tools

The search for analytical level tools for the sustainability assessment of light-duty vehicles, in addition to the recommendations for analytical level tools, revealed a number of ancillary insights. First and foremost, the suitability and relevance of any indicator or criteria must be examined with respect to what it measured and how it relates to sustainability impacts. Such a process requires critical thought and may likely be time consuming, but it prevents one from quantifying and measuring a series of criteria or indicators simply because it is available (availability bias) and then aggregating (possibly incommensurable data), either due to convention or a need for simplification. It is the responsibility therefore of the practitioner of sustainability assessment to educate the stakeholders and public of the specific characteristics of the problem (through proper problem framing and addressing systems complexity) and the areas of uncertainty or limitations in our knowledge. The selection of the objectives and criteria cannot be a static and linear process, but needs to be a dynamic one that emerges from an exchange between practitioner and stakeholder/public and the choices made need to be salient, legitimate and credible (Mitchell, Clark et al., 2006b).

The preliminary assessment of the transportation example resulted in a number of specific recommendations for the requirements for analytical level tools. First, that it is critical to undertake a lifecycle assessment of the technologies and pathways due to their various impacts at different stages. We also discussed the need for risk assessment of fuels as well as the assessment of geo-political risk – the former being quantitative while the latter potentially qualitative in nature. The possibility of using cost-benefit analysis as
a sub-assessment within scenarios of different infrastructure configurations and hydrogen production pathways, were also discussed. Additionally, non-market valuation CBA techniques such as ‘contingent valuation’ may also be necessary for estimating the value ascribed to vehicles with near-zero tail-pipe emissions and noise. Even a modified ecological footprint analysis was suggested for measuring the footprint of fuels. In addition, the use of methods not part of the SustainabilityA-Test toolbox, such as expert judgment in the estimation of air-pollution related health risks would be useful when areas of ‘scientific’ knowledge may be yet inexplicable by science.

In the transportation example chosen here the comparison of sustainability was between the various vehicle technologies and their fuel chains, which may be considered as an assessment between different technical scenarios. In other problem contexts however, the sustainability assessment could be between more elaborate scenarios. In those cases, scenario analysis would feature more prominently in the overall assessment.

The message here is that the assessment should not begin by pre-selecting a particular tool (based on ones expertise, familiarity or comfort) or set of tools and then building the assessment around that. As demonstrated, it needs to begin by first studying/analyzing the problem with the aid of some framework level tools. The result of this process will be the identification of the most appropriate tools/expertise for the assessment. Such a process will also inform and guide the public consultation process for refining the objectives and criteria as well as the options to be considered within the assessment. There can be no precise recipe to sustainability assessment, but it does not obviate the need for a sound, transparent and defensible method.
3.7 **Practical Considerations for Sustainability Practitioners**

Given the complexity of the sustainability assessment process, any attempts to hastily simplify it (to save time and resources) without consideration of the impacts of the omission could potentially jeopardize its intrinsic value. First, experience needs to be built in carrying out these somewhat complex and comprehensive sustainability assessments in different problem domains. Then it may be possible to simplify the process into sustainability heuristics, within a given domain. Such sustainability heuristics would be a valuable contribution to sustainability science (Kates, Clark et al., 2001; Swart, Raskin et al., 2004). However, it may only come after sufficient understanding and experience has been gained from conducting comprehensive sustainability assessments.

Often assessments are conducted by 'experts' who are confronted by a certain problem or are summoned to perform an assessment based on their 'expert' status. But experts are just that; those who have a special skill or knowledge representing the mastery of a particular subject\(^{54}\). Unfortunately for most experts who fit this traditional definition, their expertise for all its worth, may not necessarily qualify them to be experts in sustainability assessment – especially given the unique and complex conceptual challenges discussed earlier.

As was demonstrated in the development of the sustainability assessment framework, and its partial application to the transportation case-study, sustainability

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\(^{54}\) This may be in a particular natural/social science or in the development/application of tools within their domains.
assessment requires not only the assimilation of knowledge across multiple expert
domains but also the application of a variety of assessment tools used across a variety of
disciplines and cross-disciplines\textsuperscript{55}. The issue of tool integration will be a major challenge
for sustainability practitioners, as the tools were not originally designed necessarily for
integration with other tools. Hence it may be some time before issues of integration are
resolved. Much needs to be learned about this process.

While an attempt was made here to conduct an integrated analysis of the transportation
disciplines, at the very least a team of experts with varying expertise would be required to
conduct such a focused technical analysis. A more complete application of the
framework level tools (IA approach and MCA process) would be possible when the
above process is conducted with experts and public/stakeholder in a participatory process.
Also it is possible that several iterations of expert-only, expert-stakeholder stages may be
necessary.

It should also be noted that just as the specific tools needed for the sustainability
assessment of a given problem will vary depending on the nature and unique features of
the chosen problem (evaluand), one should expect the set of relevant expertise needed for
the assessment to also be a function of the problem itself.

The enormity of the task for future sustainability assessment practitioners is clear.
Sustainability assessment is not any assessment. If we want to do it right, we need to

\textsuperscript{55} The development of the SustainabilityA-Test itself happened over a period of 2-3 years with input from
several dozen of experts from across a variety of domains.
accept the various conceptual as well as practical challenges. Taking short cuts may only
benefit those who want to prove that they can carry out a well defined calculation,
operation or task. There is a clear need for building capacity of sustainability assessment
'experts'. Perhaps, it may require more than just a traditional engineer, economist,
environmentalist or other disciplinarian; perhaps a team in which the experts in addition
to their specific skills also have a general curiosity and aptitude for other domains/tools,
and the often underestimated social skills to interact and learn from each other as well as
from the stakeholder and public engagement process. Put it differently, what may be
required is a new breed of practitioners for a new generation of assessments.

The team of experts may be self-coordinated or alternatively co-ordinated by a lead
sustainability assessment practitioner. Each expert would understand the strength of their
respective contributions but also the importance of the contribution of other experts in the
team. Thus they would appreciate the multi-dimensional and multi-faceted nature of
problems and their particular role in the overall assessment process and not believe in a
'one size fits all' approach to sustainability assessment.

Perhaps the most important task of a lead practitioner of sustainability assessment
is in overlooking the entire process, being aware of the needs of the individual experts
and how to engage in a discussion with experts as well as the public in identifying the
sustainability context appropriate for the assessment. It is expected that the two-level
sustainability assessment framework proposed here will serve as a building block for the
next generation of assessments – sustainability assessments; and that it will be further
developed and benefit from the insights of the growing community of sustainability experts, practitioners and/or scientists.

### 3.8 Conclusions

It has been argued in this paper that the universe of assessment tools may be classified into two fundamental levels – framework level and analytical level. These may be conceived of as being part of the duality of sustainability assessments – core sustainability aspects and context specific sustainability aspects. Framework level tools embody a deeper philosophical undertone resulting in greater scope and flexibility, which enables them to compensate to some extent for the weaknesses of the more analytical tools and methods. Many of the sustainability aspects often left out by other assessments lie precisely in the space between the different analytical tools used. Therefore, assessments driven by analytical level tools only may fail to capture some of the more interesting and relevant components of sustainability. Given the value offered by framework level tools such as the IA *approach* and the MCA *process* in capturing core sustainability concerns and in assisting with the selection of the appropriate analytical level tools, their inclusion was proposed as a minimum condition for designing sustainability assessments.

Although the application of the framework level tools was only partial, it showed how the tool selection can be a result of an open, transparent and systematic process and not a result of convenience, familiarity or availability.
We also explored some of the main conceptual challenges associated with sustainability assessment, such as issues of scale, complexity, incommensurability, equity, problem framing, uncertainty, knowledge gaps etc., and showed how they relate to the framework and analytical levels of the sustainability assessment framework. Most of the conceptual challenges need to be dealt with at the framework level as they are fairly broad in scope and beyond the scope of most analytical level tools.

A number of practical challenges and considerations for future sustainability assessment practitioners were also discussed. Given the unique and complex challenges of sustainability assessment there is a need to build capacity for a new breed of practitioners. Just as the special characteristics of each problem would dictate the tools necessary, so would it require a different composition of experts for different assessments. New approaches may be necessary to facilitate integration between different sustainability assessment tools.

As discussed in this paper, designing and implementing a comprehensive sustainability assessment is a non-trivial exercise. This is so because of the many conceptual and practical challenges associated with sustainability assessment. Also, it requires the expertise as well as input and collaboration across multiple levels of stakeholders (technology experts, social-scientists, stakeholders/public, and decision-makers). Additionally, as demonstrated by the SustainabilityA-Test, there are a host of different tools available for sustainability assessment. Given the complexity and challenges mentioned above, this paper attempted to contribute a small piece toward the specific
challenge of tool selection, in the overall sustainability assessment process. Similarly, close attention may be necessary to improve other aspects of the overall process (building capacity, public engagement, improvements in the communication to stakeholders/decision makers, improvements in how to select stakeholders, improvements in individual tools to be more compatible for tool integration etc.), in order to collectively contribute toward the science of sustainability. Anyone who may have expected the process of sustainability assessment or the science of sustainability to be easier, would have seriously underestimated the sustainability challenge.
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4 Bridging the Gap – a retrospective analysis for guiding future energy and socio-technical change

4.1 Introduction

Hydrogen was discovered in 1766 and the Fuel Cell in 1845, yet it took more than a century after its invention, before the first hydrogen-powered fuel cells were used in any practical application, namely the Apollo and Gemini Space missions of the 1960’s (Bellona Institute, 2002). Hydrogen was used as a chemical for various industrial purposes and exploited for its lighter than air properties in military applications (i.e., wartime dirigibles) throughout the 20th century but only in the 1970’s, after the oil crisis, did the idea of a hydrogen-economy emerge into what was then called the “hydrogen movement” (Veziroglu, 2000). This notion however, had more to do with hydrogen’s energetic properties than with its original interest as a chemical or for being lighter than air.

A hydrogen economy may be thought of as a future economy where a large fraction of the energy system supporting the economy is based on hydrogen (or hydrogen-rich energy carriers). In order to utilize the energy contained within hydrogen, energy conversion devices such as fuel cells may be considered as being part of such an energy system (powering vehicles, providing electricity and heat for buildings, industrial and commercial energy etc.). Although the interest and investment in hydrogen (and fuel cells) of the 1970’s faded as the price of oil returned to the pre oil crisis levels in the subsequent two decades, more recently, due to growing concerns over the climate and local air-pollution impacts of the fossil-fuel based regime as well as concerns over the

56 A version of this chapter has been submitted for publication to the journal Energy Policy.
geo-politics of petroleum (i.e., energy security), another wave of enthusiasm has emerged over the prospects of a future hydrogen economy. While some believe this vision to become a reality within the next 2 decades (Bockris, 1999; Clark & Rifkin, 2006; Vezirioglu, 2000), others are either cautiously optimistic or sceptical about its prospects (Hammerschlag & Mazza, 2005; Keith & Farrell, 2003; National Research Council USA, 2004; Suzuki, 2004a).

Supporters and believers of a future hydrogen based energy system urge governments and industry to invest today in hydrogen and fuel cell based technologies so that today's energy systems can make the transition into a hydrogen based energy future. A number of different arguments have been made in favour of a hydrogen future, including the direction of global decarbonisation trends, the shift towards fuels with higher hydrogen to carbon ratios, the shift from solid to liquid to gaseous fuels, reduced climate change impacts and health impacts from local air-pollution, improved geo-politics of energy, and a host of other expected sustainability benefits. Indeed an undeniable trend of global energy systems has been its decarbonisation. However, if global decarbonisation rates are analyzed over a few centuries it becomes clear that the pace of decarbonisation has been glacial at only 0.3% per year (Grubler & Nakicenovic, 1996). Therefore, this implies that a transition to a carbon-free hydrogen energy future from today's fossil-energy signature may not be just around the corner.

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57 Decarbonization is a trend towards overall reduction in carbon intensity, where carbon intensity is the amount of carbon released into the atmosphere per unit of energy used.
While the hydrogen futures literature is used as the medium for the discussion of future energy transitions, this paper is not about whether we should pursue a hydrogen future, but about the considerations that may be needed in order to think about future energy and technology transitions in the context of socio-technical change. To this end we draw from a number of different literatures that have probed our energy and technology past, in search of patterns, mechanisms, lessons, etc., with the aim of improving our understanding of technology, its societal context and its diffusion and transition dynamics. In particular, in section 4.3 we will discuss the insights revealed from the literature on socio-technical transitions, diffusion of systems of technologies and infrastructures and on the modelling of technical change (TTDM)\(^{58}\). This will be followed by (in section 4.4) the application of these insights and building blocks to energy technology policy across 3 temporal dimensions: past policy experience, present guidance for a hydrogen transition and finally some thoughts on the guidance for future transitions. We will conclude with some recommendations for thinking about future transitions. But first, in section 4.2 we will explore the notion of a hydrogen economy and some of its special characteristics relevant to our discussion.

\section*{4.2 Back to the Future – The Hydrogen Economy}

The term ‘hydrogen economy’ although used widely in the energy and hydrogen literatures, is rarely defined. As mentioned earlier, while we may conceive of it as a future economy where a large fraction of the energy system supporting it is based on hydrogen and some combination of hydrogen (or hydrogen rich energy carriers) and fuel...
cells, across its various sectors, according to (McDowall & Eames, 2006a) the term ‘hydrogen economy’ can take multiple meanings. This is partly due to the fact that there are a large number of renewable and non-renewable primary energy sources that may be converted to hydrogen (different pathways) as well as two major system configurations (centralized production with pipeline delivery and de-centralized production) for system design. Thus depending on the particular pathway as well as hydrogen storage and delivery options chosen different manifestations of a hydrogen economy are possible (Ogden, 1999b; Pembina, 2002). While in theory different hydrogen economies may provide similar functions (i.e. in terms of services), in form they may be quite different.

4.2.1 The Demand side and the Diffusion Barrier

Maintaining the diversity on the supply side may be a desirable feature, but for a given region only a limited number of hydrogen production pathways may be feasible. However, implicit in the notion of a hydrogen economy, is that on the demand side (transportation, power generation etc) hydrogen is utilized in some combination with different fuel cells. While a hydrogen atom (a proton plus an electron) will be indistinguishable from its source to the consumers (like electricity - flow of electrons), the same fuel cell may not be used across the different demand side applications. This is because a variety of different fuel cells exist with different operating temperatures (ranging from room temperature to 1000 deg C), input fuels (pure hydrogen as well as methanol, natural gas, other fossil fuels and even carbon monoxide), materials and engineering requirements. These differences in fuel cells are primarily due to the different energy services they provide in different application domains or sectors of the
energy system, such as mobility in transportation\textsuperscript{59}, heat/power in stationary applications (kW-MW range) and power in portable electronic devices (<100 W). Differences also exist due to their different stages of development.

While the supply side has its particular techno-economic challenges, the end-user is mostly in contact with the demand side or end-use technologies, such as fuel cells. From an end-user perspective it is interesting to note that the different fuel cell applications (within different energy service domains) vary significantly with respect to a number of socio-economic and socio-technical criteria that may be relevant to their ultimate diffusion (see Table 4-1).

The centralized hydrogen production architecture for fuel cells in transportation would require costly pipeline infrastructure and although the decentralized hydrogen production would not require such pipelines, the technical requirements for hydrogen production, storage and dispensing demand major advances in technology, technology implementation and standardization (hence the +++ for transportation technology requirements in Table 4-1). On the other hand, fuel cells for stationary applications can use existing infrastructure (natural gas and electricity grids) while portable applications don’t require any. Given the more complex technical requirements for fuel cells in transportation and the current state of PEMFC technology, the cost differential between fuel cells and its conventional counterpart (IC engine) is also highest in the transportation sector followed by the stationary and portable sectors. These two parameters alone

\textsuperscript{59} Further disaggregation may also lead to additional insights, such as the suitability of hydrogen and fuel cells in different transport modes - heavy-duty freight, light-duty vehicles etc., (Farrell & Keith 2003).
provide an indication of the differences in the current diffusion barrier across the 3 different fuel cell application domains\textsuperscript{60}.

<table>
<thead>
<tr>
<th>Market</th>
<th>Technology Type\textsuperscript{61}</th>
<th>Cost Differential\textsuperscript{62}</th>
<th>New Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>PEMFC</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Stationary</td>
<td>SOFC</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Portable</td>
<td>DMFC</td>
<td>+</td>
<td>+ + +</td>
</tr>
</tbody>
</table>

Table 4-1: Fuel Cell application domains and their characteristics for Technology Diffusion

For all columns, except public perception ‘+++’, ‘++’ and ‘+’, represent high, medium and low qualitatively for the column heading.

The 3 different application domains also differ in terms of the amount of new functionalities they offer to the potential technology adopter. Fuel cells in portable electronics such as laptops, provide the consumer the convenience of instant re-charge (by simply replacing methanol cartridges) and extended duty-cycle or operation time (approx. 3-20 times longer). In addition, they provide environmental benefits such as the elimination of the environmental impacts of discarded batteries and avoidance of the high-costs of recycling. These new functionalities may provide saved opportunity costs that could help counter some of the drawbacks such as potentially higher cartridge costs.

\textsuperscript{60} It should not be assumed that this barrier will remain fixed over time. As we will discuss in later sections, depending upon the changes occurring in the socio-technical landscape and regimes, each of these parameters may vary.

\textsuperscript{61} The acronyms stand for, Polymer Electrolyte Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC) and Direct Methanol Fuel Cell (DMFC).

\textsuperscript{62} The cost-differential refers to the ratio between the capital-cost of the technology to that of its major competitor. The operational-cost differential was left out from this table as the capital-cost differential tends to dominate the operational-cost differential. The reason why it is important to consider the cost-differential for a given application domain is because our current willingness to pay for a kilowatt of power is vastly different across these application areas. While we presently pay on the order of $50/kW for the internal combustion engine (ICE) in automobiles, we pay upwards of $1000/kW for batteries in portable electronic devices. Therefore a fuel cell that costs $5000/kW in the transport sector would see a cost-differential of 100 while if its analogue in the portable application cost the same, it would see a cost-differential of only 5. Thus, in this example, as far as direct costs are concerned the diffusion barrier would be far smaller in the latter.
(compared to the low costs for charging batteries with electricity) or the toxicity of methanol\textsuperscript{63}.

In short, the application with the lowest technology requirements and cost-differential, offering the greatest improvements in functionalities may appear to be more favourable to the public\textsuperscript{64}. Thus if the goal is indeed a hydrogen economy that pervades the energy sector, then explicit consideration of the different diffusion barriers for demand side technologies may be relevant for policy. Therefore, considering the combined heterogeneity of the supply and demand sides, it may be prudent not to treat the hydrogen economy as a homogeneous and unambiguous term, in order to improve policy effectiveness. However, as we will see in the following sections, even these considerations may not be entirely sufficient, as they somewhat conceal and belie the larger context of socio-technical change.

4.3 Insights from TTDM - The Missing Links

Connections between TTDM and hydrogen energy futures or ST-futures in general are relatively sparse. (McDowall & Eames, 2006a) in a review of the hydrogen futures literature remark how only four out of forty studies made any reference to the theoretical literature on technological change. Also, according to (Godoe & Nygaard, 2006) “…this technology [hydrogen and fuel cells] has not been widely studied, especially not from an innovation standpoint.” Partial exceptions in this area are (Hisschemoller, Bode et al.,

\textsuperscript{63} This problem may be dealt with by developing a leak-proof cartridge technology and by regulating proper practices for its safe transport, similar to our usage of cigarette lighters.

\textsuperscript{64} The impact of public perception of hydrogen and related energy technologies and their perceived risk is a growing area of research. The following is a list of suggested reading on this topic: (Flynn, Bellaby et al., 2006; Ricci, Newsholme et al., 2007; Shackley, S., McLachlan et al., 2005).
2006) who from the perspective of political theory explore the relationship between technologies and institutions based on different paradigms of governance\textsuperscript{65} and their possible bias with respect to hydrogen options, (Shackley, Simon & Green, 2007) who discuss the changes in the UK energy system over the past several decades from the perspective of technological transitions and (Kemp & Rotmans, 2004) who use the policy perspective of transition management to explore solutions for sustainable passenger transport.

In this section three sub-sections of the TTDM literature, which are often dealt with in isolation, will be explored (sections 4.3.1 to 4.3.3) for their collective insights relevant to future transitions and ST-change. In so doing we hope to contribute toward bridging this gap between the literature on technical change and ST-transitions. While these sections are not meant to be a comprehensive review of the respective literatures, they represent the components that are relevant for the discussion on future energy transitions, and ST-change.

4.3.1 Technological Transitions and the Multi-Level Perspective

The intrinsic linkages and interaction between technology and society is emphasized in the literature on science and technology studies (STS) (Bijker, Hughes et al., 1987), and its various derivatives, such as Large Technical Systems Theory (LTS) (Hughes, 1983, 1987), Actor-Network Theory (ANT) (Callon, Laredo et al., 1992; Latour, 1987) and in the literature on the Social Construction of Technology (SCOT) (Bijker, 1995; Pinch &

\textsuperscript{65} Namely 'Governance by policy networking', Governance by government', 'Governance by corporate business', and 'Governance by challenge'.
Bijker, 1987). This literature emphasizes the societal context of technology - that it is “socially shaped and society shaping” (Hughes, 1987). With this understanding technology change or transitions in technological systems may be thought of as occurring in a conceptual space of ‘socio-technical systems’, where the various elements of society (existing technologies, innovations, rules, regulation, culture, systems of beliefs, etc) link with each other in ‘configurations that work’ (Rip & Kemp, 1998) to fulfill various societal functions (energy supply, transportation, health-care etc).

Building on the work by (Rip & Kemp, 1998) on the notion of technological niches, regimes and landscapes, (Geels, Frank W., 2002, 2005) introduces a multi-level perspective (MLP) consisting of socio-technical niches (ST-niche), socio-technical regimes (ST-regime) and socio-technical landscape (ST-landscape) as a nested hierarchy, where regimes are embedded within landscapes and niches within regimes. Such a framework consisting of these levels may be used to understand system innovation and socio-technical change.

Figure 4-1 provides a schematic representation of this framework. The ST-niche is a protected space where novelties may be developed and learning may occur with the expectation of future application. It is reasonable to expect radical innovations particularly, to need such protection as they may be viewed as ‘hopeful monstrosities’

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66 The notion of a niche may be differentiated into technological niche and market niche (Geels 2005). Although a niche technology could be operating in either of these niches, in the case of the former it may be sustained by subsidies and strategic investments while in the latter it may be sustained by regular markets (although small) on their own or in combination with subsidies and strategic investments. Also in the former, design rules and users are often not properly defined or articulated and thus are more unstable than the latter. Hereafter, unless otherwise specified, the term niche refers to both types.
(Mokyr, 1991). The significance of the niche in the multi-level perspective is that it serves as the seed for regime change (Kemp, Schot et al., 1998). Whenever there is instability or tensions within the ST-regime due to its own internal dynamics or due to pressures from the landscape level, radical innovations in the niche level can take advantage of these tensions and break into regular markets. As such, when novelties emerge they emerge within the context of the rules of the regime and its specific problems.

![Figure 4-1: Niches, Regimes and Landscape in the Multi-Level Perspective. Source (Geels, Frank W., 2004).](image)

The rules of the regime bring it stability as they act as barriers to actions not consistent with it. However stability is not automatic as rules may need to be reproduced and re-affirmed in order to maintain their status. An interesting analogy is made by (Geels, Frank W., 2005) between regime rules and neural networks in the brain: "Connections in neural networks grow stronger or weaker as they are used more or less frequently."
Connections may even die out if not used at all. Likewise, rules change as they are used. Rules that are no longer used gradually die out”. As such rules may be modified and re-interpreted as a result of the multiple interactions between the actors of the regime. Geels also describes the concept of the socio-technical regime as being composed of the technological regime, user and market regime, socio-cultural regime, policy regime and science regime.

The ST-regime exists within the context of the ST-landscape. (Rip & Kemp, 1998) used the metaphor of the landscape to introduce the concept of socio-technical landscape in order to represent the ‘hardness’ or the material context (the built environment) of society. The concepts of ST-landscape also contains a number of heterogeneous aspects such as social values, policy beliefs, worldviews, political coalitions, prices and costs, trade patterns, incomes, wars and environmental problems. From an analytical standpoint landscapes may be thought of as forming gradients for action. This means that landscapes make it easier for socio-technical developments to move in particular directions over others.

The MLP emphasizes the dynamic interactions between these multiple levels, the outcome of which is structural and socio-technical change. It should be pointed out however, that in terms of influencing change, from the perspective of MLP, the ST-landscape is considered to be beyond the direct influence of actors from the ST-regime (Geels, Frank W., 2004), although it may have a large influence on activities and
practices within the ST-regime and the ST-niche. This point however, will be contested shortly.

As far as technological transitions are concerned, niches are also viewed by proponents of Strategic Niche Management (SNM) as protected spaces for learning about the new technology in order to support its controlled phase-out from niche to regime (Kemp, Schot et al., 1998). SNM may be viewed as part of a broader approach to the management of transitions - Transitions Management (TM). Here the focus is on a transformation of the entire society or socio-technical system. While TM stresses that no single actor can steer a transition and that it has to be a collective process, it does emphasize the guidance from actors within the niche.

This guidance and bottom-up approach to transitions from niche-to-regime has been criticised in the literature for being too reliant on solutions grown in niches (Berkhout, Frans, Smith et al., 2004). In addition to this bottom-up approach (niche-to-regime), transitions may also occur due to influences from the landscape downward on the ST-regime in a top-down fashion. For, instance (Berkhout, Frans, Smith et al., 2004) have argued that while the social movement for Alternative Technologies sought a process of change more consistent with the niche-based model, the wider environmental movement sought more directly to influence changes at the higher ST-landscape level (and regime level) of institutions and economic structures. In section 4.4.1 we will also present a more top-down approach to guiding socio-technical change in contrast to the traditional technology-driven nature of past policy and guidance for socio-technical transitions.
In the remainder of this paper, technological transitions and socio-technical change will be discussed from the point of view of one or more of the 3 levels of the MLP. Thus, they will serve as an important linguistic and conceptual aid for the discussion.

4.3.1.1 Niche based Transition Dynamics – empirical examples

Technological substitution (based on logistic curves) and economic substitution (based on learning curves) of an old technology replacing a new one, has been argued by (Geels, Frank W., 2005) to be somewhat simplistic, to the extent that they focus primarily on technology and markets without saying much about how the new technology emerges and the dynamics earlier on in the substitution process. Citing the example of how steam engines first entered sailing ships as an auxiliary device, effectively enhancing the functionality of sailing ships, Geels argues that the new technology can form a relationship of symbiosis (or complementarities) with the old – thus forming a hybrid technology. As the performance of the new technology improves, it may render the old technology as the auxiliary device and eventually compete and substitute the old. Similar examples of technology symbiosis are seen in the transition from steam engines to electric motors in factories/industry and between gas turbines and steam turbines in combined cycle gas turbines (CCGT) (Geels, Frank W., 2005; Isla, 1997).

The reasons for why the steam engine was first incorporated into sailing ships had to do with the need for improving the speed of mail-transport. Eventually taking advantage of the increased demand for mass emigration between Europe and USA in the 19th century, steam-engines were able to breakout of the mail-transport niche and the symbiotic
relationship to dominate the oceanic transport market in steamships. In the MLP perspective, such transitions are thought to take place due to the linking up of niche activity with landscape events (European emigration) through a process of gradual reconfiguration of the socio-technical regime (Geels, Frank W., 2002, 2005). The European emigration was in turn created by the Irish potato famine, European political revolutions and the Californian gold-rush.

Similarly it has been argued by (Berkhout, Frans, Smith et al., 2004) that steamships linked-up and helped resolve tensions/bottlenecks (such as the irregularity of wind-powered sailing ships) within the incumbent ST-regime that had constrained further development. Thus niche technologies may be able to link-up with developments directly from the ST-landscape level or from the ST-regime level (potentially resulting from landscape developments) and create alternative trajectories for regime development. However, the creation of such opportunities to link-up with niche technologies may be somewhat out of the control of the regime actors (as well as for those outside the regime), limiting their ability to steer technical and socio-technical change.

With regards to the substitution of sailing ships, it is interesting to note that they did not concede defeat easily. During the 1860s and 1870s when they were challenged by steamships, they fought back fiercely with a high level of innovation within the industry (Geels, Frank W., 2002; Victor, Heller et al., 2003). This effect has been termed the sailing-ship effect. Although this rebuttal helped in slowing down the diffusion of steam
ships, in this example, the new technology eventually captured and dominated the market.

The market deployment and acceptance of the hybrid gasoline-electric automobile (due to a variety of technological as well as landscape developments) may thus be seen as a symbiotic relationship which may enable the electric motor to improve performance and increase acceptance in the transport sector, or as a strike back (sailing-ship effect) pre-emptively (against the emergence of a hydrogen and fuel cell based energy system) by the existing ICE-gasoline regime, in order to continue its dominance. Thus, the above discussion points to the importance of viewing future transitions as not simply a process whereby the old is replaced by the new, but as being somewhat more complex especially in the early phases of diffusion.

4.3.1.2 Regional ST-regimes and the MLP

The MLP provides a high-level conceptual aid for discussing socio-technical transitions. However it does not provide the spatial resolution that largely differentiates real-life socio-technical systems. One could argue that this is a weakness of MLP, if one takes the view that all frameworks, models and concepts must be applicable at all relevant levels (low and high resolution); but there exists no such rule, nor would there be a sound basis for it. Therefore, the position taken here is that although the MLP operates at a high-level of conceptual aggregation, it can be applied to different regional contexts to analyze their particular ST-niches, ST-regimes and ST-landscapes, and therefore the lack of spatial resolution is not seen as an inherent weakness.
In section 4.2 we discussed the importance of recognizing the heterogeneity of the hydrogen economy (i.e. demand side characteristics) and its implications for technology diffusion. Similarly, it is important to recognize that different regions as well as nations have completely different ST-regimes as well as underlying ST-landscapes. Therefore, it is likely that the outcomes will be very different as will their rates of success.

The creation of a hydrogen economy is often seen as a race by some ST-regimes and a bandwagon to be jumped on. Iceland became the first country when in 1999 it proclaimed its goal to become the world’s first hydrogen economy by 2030 (Árnason & Sigfússon, 2000; Dunn, 2001). Iceland is a small and homogeneous population (less than 300,000), abundant in geothermal energy and with limited to no availability of fossil fuels and other resources as well as being located at a distance from major markets. The culture and the various regime actors within it generally favour alternative energy systems and technologies and are generally resource conscious. The large geothermal resource (a commercially viable resource and technology, presently producing low-cost electricity) provides a renewable source of energy for the production of hydrogen sustainably for a long-time, especially given the small size of the nation. Given these particular characteristics of the ST-landscape and the regime, Iceland may be conducive to a sustainable hydrogen energy future in the relative near-term.

While Japan is also aggressively pursuing a hydrogen energy future, its ST-landscape and ST-regime is entirely different with a population several orders of magnitude larger, spread over thousands of islands and with no low-cost renewable energy source for
hydrogen production. Japan also is not endowed with large fossil fuel and other resources. Since nuclear power is already in use in Japan and if the public further supports nuclear power for hydrogen production, then it may produce hydrogen with little to no emissions of GHG. As such given the different conditions (i.e. geography, history, resource endowments, political conditions, public perception etc) existing within any given nation, the most sustainable ST-transition paths could be quite different. It may also be worth noting that there could also be a difference between the most sustainable and most desirable ST-transition path.

While it is acknowledged that entirely different regime and landscape conditions than Iceland may also find the goal of a hydrogen economy conducive, if regime actors (hydrogen transition proponents and policy-makers) appreciate the supply and demand side heterogeneity within the hydrogen and fuel cell space, as well as the complexity of the transition process, they are likely to be better informed and better equipped to deal with the challenges of technological transitions. This suggests the possibility of different transition contexts being relevant for different regions. The notion of ‘transition contexts’ will be discussed further in the next section.

4.3.2 Diffusion of Systems of Technologies and Infrastructures

This section will discuss the literature on large-scale technical systems, the notion of technology lock-in, and the diffusion of infrastructures and technological clusters as they relate to socio-technical transitions. The general literature on technology diffusion will not be discussed here as it pertains mostly to theories and models of various diffusion processes for individual technologies and innovation processes within firms or on the
economics of technology diffusion. Given that this literature is only loosely connected to questions about large-scale socio-technical change, it will not be explored here\textsuperscript{67}.

**Large Technical Systems (LTS):** The literature on LTS emerged primarily as a result of the work by (Hughes, 1983, 1987). As the name implies, the focus was on large technical systems such as electricity networks, telephone networks, railroad networks, internet etc., which stretch vast geographical expanses. From the point of view of this research it is also interesting to note that LTS is not just about technology, but has a socio-technical mode of analysis. The notion of *seamless webs* introduced by (Hughes, 1986) consists of various linkages between heterogeneous elements such as technology, firms, society, contracts, legislation etc., that work together to form socio-technical configurations.

While (Hughes, 1987) distinguishes five phases in the development of the LTS: (a) invention (b) development (c) innovation (d) growth, competition and consolidation (e) momentum, it says little about the decline of LTS, suggesting that systems last forever after reaching the momentum stage. As we will see from the empirical literature on the diffusion of large scale infrastructures and from the analysis of inter-sectoral diffusion processes, all technological systems are characterized by a time-constant related to their life-span. This decline may be thought of as weakening linkages, between the various elements of the socio-technical configuration that may provide opportunities for socio-technical change.

\textsuperscript{67} For a review of this literature, the reader is referred to: (Everett, 1995; Fagerberg, Mowery et al., 2006; Geroski, 2000; Griliches, 1957; Sarkar, 1998; Stoneman, 2002).
In a retrospective analysis of Large Technical Systems (Joerges, 1988) discusses how the emergence and transformation of LTS consists of complex processes of co-evolutionary elements. He suggests that this complexity of LTS surpasses the capacity for reflexive action by the major actors responsible for operating, regulating, managing and redesigning it, as they may be unable to form a complete picture of its workings. This insight bears resemblance to the concerns raised by (Berkhout, Frans, Hertina et al., 2002) about the problems of indeterminacy, discontinuity, reflexivity and framing of socio-economic systems. Collectively these concerns highlight some of the challenges of the transition management and strategic niche management approaches. The implications of the above observations are two fold: (a) that the sheer complexity of the intimately interwoven large technical and social systems that make up socio-technical systems make it near impossible to have a complete or even reasonable understanding of it and (b) that novel concepts, methods or approaches may be necessary to guide our thinking about transitions and socio-technical change.

The MLP is certainly an important contribution to this end. Another important contribution is the transition contexts of (Berkhout, Frans, Smith et al., 2004). We will digress briefly to describe these transition contexts as it will be useful for our subsequent discussion. Berkhout et al. propose a framework consisting of four different transition contexts that may be conceptualized as existing in one of 4 quadrants created by two axes: (a) the degree of co-ordination of regime actors (high/low on x-axis) and (b) the resources available to the regime (within the regime or outside it) to respond to selection pressures (internal/external on y-axis). The four resulting contexts are labelled ‘purposive
transitions’ (deliberate change caused by actors outside the regime), ‘endogenous renewal’ (deliberate change fostered by regime members), ‘re-orientation of trajectories’ (spontaneous change resulting from relationships and dynamics within a regime) and ‘emergent transformations’ (the unintended consequence of changes wrought outside prevailing regimes). Finally, regardless of the degree of co-ordination (and the pressures from the niche or landscape levels) according to Berkhout et al. the adaptive capacity of the regime may be crucial to the type of structural change and transition that may occur. In their own words, “If the resources to adapt are available internally, then change is likely to be more incremental and structural relationships within the regime are less likely to be overturned. If the capacity to adapt is highly constrained by the lack of resources internally then the opportunity for major structural change exists.” (Berkhout, Frans, Smith et al., 2004).

These transition contexts should be seen as adding a more diverse range of transition pathways than the bottom-up niche-to-regime transformation discussed in the MLP and transition management literatures. We hope to expand on these developments by exploring the literature on technical change for insights relevant to socio-technical transitions. In the remainder of this section we will explore some empirical data on the diffusion of transport infrastructures, inter-sectoral diffusion processes, technological cluster analysis and the concept of technological lock-in. Comparisons will be made to hydrogen energy systems and futures as appropriate. As we will see, this exploration will provide important insights about past infrastructures, their intrinsic properties and on the dynamics of their transitions.
Diffusion of Transport Infrastructures: As pointed out earlier, (Geels, Frank W., 2005) criticized simple substitution models (based on logistic curves or learning curves) as they say little about the dynamics earlier on in the substitution process. Nevertheless logistic curves (which are entirely descriptive) that plot cumulative market penetration over time\textsuperscript{68} offer important information about timescales involved in diffusion processes. Using logistic curves to analyze transport infrastructures over the past 200 years (Nakicenovic, Nebojsa, 1991) uncovered the time-constants ($\Delta t$) for canals to be roughly 30 years while for railroads and surfaced roads they were 54 years and 56 years respectively (all values are for USA).

On the other hand $\Delta t$ for automobiles (replacing horses) was only 12 years in the USA. Although this relatively short $\Delta t$ for cars at first may be seen as evidence in favour of short diffusion time-frames for Fuel Cell Vehicles (FCV), such a view may be somewhat simplistic. While technologies tend to diffuse faster within a common infrastructure\textsuperscript{69} (Grubler, Nakicenovic et al., 1999), the fuel production and delivery infrastructure would not be common between FCVs and Internal Combustion Engine Vehicles (ICEV). When making the transition from horses to automobiles (horseless carriage) although large changes in fuel production and delivery were also required, one major difference was that there was a substantial increase in performance of passenger mobility in terms of convenience, speed, touring etc., offering new functionalities to the consumer. Since

\textsuperscript{68} These result in the classic "S" shaped diffusion curves.
\textsuperscript{69} Such as in the diffusion of catalytic converters ($\Delta t = 12$ yrs) in cars and in the substitution of steam by diesel-electric locomotives ($\Delta t \sim$ one decade).
FCVs are unlikely to create a substantial increase in functionalities in terms of passenger mobility, given the different infrastructure requirements, it is unlikely that FCVs will have short Δts as ICEVs did. This however, may point to the importance of demonstrating the FCVs performance perhaps in terms of its sustainability\(^70\) (Roberts & Robinson, 2007) in order to gain a competitive advantage and thus public acceptance.

**Inter-sectoral Diffusion Processes:** By plotting the cumulative frequency distribution of 265 diffusion processes in the USA over the past 200 years, including technological innovations as well as a host of inter-related technological, institutional and organizational products and services, (Grubler, 1991) also uncovered some interesting points of reference. Not surprisingly the Δt ranged from a few years to a few centuries, while the mean value for Δt was 41 years with a standard deviation of 42 years\(^71\). For 50% of the diffusion processes Δt < 30 years, while for 93% of the diffusion processes Δt < 100 years. Time constants for the diffusion of infrastructures and entire technology clusters spanned up to a century. According to Grubler, the greater the infrastructure needs, technology inter-dependence, and the pervasiveness of a given technology or system the longer will be the diffusion process.

\(^{70}\) Sustainability benefits will need to be demonstrated both upstream and downstream.

\(^{71}\) Similarly (Victor, Heller et al. 2003) analyzed the Δt of a variety of technologies, infrastructures and primary energy sources. Considering the Δt for DRAM (Dynamic Random Access Memory) of 5 years and over 200 years for coal, in comparison to all other technologies and infrastructures in between, they estimate that Δt for hydrogen is no less than four decades (Δt > 40 years). Incidentally, Victor et al.'s lower limit for the Δt for hydrogen roughly matches with Grubler's average Δt of 41 years across 265 diffusion processes. It is not clear if their Δt for 'hydrogen' is meant in the collective sense of the term (all application domains) thus being representative of the shortest diffusion, or if this lower limit as a rough bounding analysis would hold for each of its application domains.
The implications of this for a hydrogen transition are as follows. If hydrogen (and related technologies) is to be the basis of a future economy, then by definition it is expected to be pervasive in nature. Pervasiveness implies complex interdependencies technologically as well as well as in terms of the underlying rules/logic/grammar of the socio-technical regime. While there is no doubt feedback between the two, it may be the latter that actually enables the former and not the other way around. While it is true that hydrogen and fuel cells have never been cost-competitive with the incumbent technologies in the ST-regime, reduction in costs alone may not enable pervasive diffusion unless the rules that govern the ST-regime facilitate technological inter-dependence and eventual emergence of the compatible innovations and technologies from the ST-niche into the ST-regime (we will return to this point in section 4.4 and 4.5). The new rules of the ST-regime may not necessarily shorten the long-time frames for pervasive diffusion, but may simply enable it. Further insights about the rules of ST-regimes can be obtained through the analysis of technological clusters.

Technological Clusters: Technological clusters are a set of inter-related technologies and infrastructures. Clusters form as technologies and infrastructures co-evolve and co-develop while building synergies with each other (according to the MLP, infrastructures and clusters thus form the increased structuration of the ST-landscape – Figure 4-1). This process of inter-locking essentially determines the selection of compatible technologies (technology lock-in) and builds high barriers and costs for incompatible products and processes (Grubler, Nakicenovic et al., 1999).
In an analysis of technologies and technological clusters over the past 200 years (Grubler, Nakicenovic et al., 1999; Nakicenovic, Nebojsa, 1991) report three clearly distinguishable clusters of technologies. The first saturated (top end of the S-curve) around 1865 (canals, water power, sails, iron-casting, turn-pikes), the second around 1930 (railways, steam-ships, telegraph, heavy duty industry), and the third is apparently saturating now (electric power, oil, cars, radio, TV, petrochemicals).

In section 4.3.2.1 we discussed the importance of the rules in the ST-regime and how it facilitates the interdependencies between compatible technologies. At a higher level of technology aggregation as shown from the formation of technology clusters, the rules and practices of the ST-regime are in turn influenced by the underlying rules and compatibilities of the clusters. If the observation by (Grubler, Nakicenovic et al., 1999) of a presently saturating cluster is indeed true, then such a process of disruptive crisis (saturation or senescence of the cluster) can provide the fertile ground for new systems to develop (Nakicenovic, Nebojsa, 1991). In other words, this refers to a window of opportunity where if choices are made in a consistent manner, then an opportunity seems to exist to influence the rules of the ST-regime that might facilitate another systems transition. However, given the different contexts for transition (Berkhout, Frans, Smith et al., 2004) described earlier, a number of different factors may guide the direction. We will elaborate on this point in section 4.4.

With regards to the discussion on systems of technologies and infrastructures so far we have looked at LTS, diffusion of transport infrastructures, inter-sectoral diffusion

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processes. Another intrinsic feature of large technical and socio-technical systems is that of technological lock-in.

**Technological Lock-in:** The inter-locking nature of particular technologies and infrastructures along certain trajectories is referred to as technological *lock-in* in various literatures. This constrained aspect of technology evolution is also sometimes called path-dependence (PD)\(^{72}\). Another interpretation of PD suggests that insignificant events by chance may give one technology (not necessarily superior) the market or diffusion advantage over another (Arthur, Brian W, 1989). The MLP and transitions theory on the other hand would interpret PD as the gradients of the landscape that make some advances easier than others.

(Cowan & Hulten, 1996) discuss technological transition as a process which overcomes or escapes from technological lock-in and suggests it being possible depending on the occurrence of six extraordinary factors: (1) a crisis in the technology involved (2) regulation (3) technological breakthrough (4) changes in taste (5) niche markets and (6) scientific results. While they cite examples from the failure of some pesticides in agriculture, regulation about CFCs in refrigerators, breakthrough of factory automation and general arguments on changing tastes, niches and science, it does not provide any guidance on how socio-technical transitions may emerge - especially since the discussion is driven by an emphasis on technologies. As such selective examples of technologies

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\(^{72}\) Technological inertia and stability are also used interchangeably to refer to lock-in and path-dependence.
from particular industries viewed in isolation cannot be considered as large-scale trends in technical systems or ‘rules of thumb’ for ST-transitions.

Also, it should be noted that given the complexity of ST-systems and transitions, taken individually none of the above six factors alone were responsible for any transition, nevertheless (Cowan & Hulten, 1996) discuss these factors individually and ignore the possible interplay between these and other factors that could possibly lead to a transition. Finally, analyzing each factor separately, in the context of a possible escape from a gasoline automobile system (considered as locked-in due to path-dependence from early economic and technical factors) to an electric vehicle system, they conclude that none of the factors favour such an escape (transition) from the lock-in to the gasoline vehicle, at least not any time soon.

(Unruh, 2000) introduces the notion of a Techno-Institutional Complex (TIC) which he describes to be a result of the combined interactions of technological lock-in of technological systems and institutional lock-in of private and government institutions. He coins the phrase carbon lock-in to describe the fossil-fuel based techno-institutional complex of today’s industrial economies. While he describes the carbon based TIC as creating formidable barriers which essentially locks-out alternative carbon-saving technologies, he emphasizes that this is not a permanent condition and based on history “they can only delay the time when these technologies will be replaced by new dominant designs that resolve the existing environmental contradictions.”
In the context of climate policy, in a follow-up article (Unruh, 2002) recommends SNM as a policy option for escaping carbon lock-in. However, he does acknowledge several problems with the niche based approach: (a) the cost-effectiveness criteria upon which technologies emerge from niches is not an objective criterion as it depends on the incentive/disincentive structure established within the TIC (b) niche technologies need plenty of time to incubate before the market conditions become favourable and that that time may be too long for implementing much needed climate solutions. He also alludes to the fact that niche solutions may appear better suited to deployment of particular technologies and that "....it is obviously more difficult to find a “niche” for an entire technological system". This difficulty is only amplified if one tries to find a niche for an entire socio-technical system. Put it another way, what operates within a technological niche is a particular technology and a socio-technical system is not simply a collection of technologies that emerge from niches into the regime. As discussed in section 4.3.1 guiding a transition toward a desirable ST-regime is not the same as moving toward a random or incoherent set of technologies that emerged from niches. Thus a ST-regime may be considered as operating at a much higher level of aggregation, than at the level of technology. We will build-up on this point in section 4.4.1.

An interesting example of a possible technology lock-in, within the realms of hydrogen futures, comes from a study of German R&D in hydrogen energy systems over the past 30 years (Hekkert, van Giessel et al., 2005). The authors warn about a premature lock-in to a sub-optimal hydrogen energy future (in the transport sector) due to an apparent emphasis by industry on too few technological options, which they consider to be sub-
optimal and unsustainable. They suggest that technology variety is particularly important during early stages of innovation and that flexibility in the choice of technology is necessary to prevent a transition and lock-in to a sub-optimal hydrogen energy system. As we will see in section 4.3.3, this point about technology variety (not just hydrogen technologies) is also a result that emerges from the technology modelling literature.

It should be noted that while the concept of technology lock-in is often seen as an undesirable feature in the evolution of technical and socio-technical systems, it is not necessarily so. There are always industries that benefit economically from sub-optimal technical and socio-technical systems. While those industries may not have single-handedly been responsible for the lock-in, as the lock-in established itself more firmly their ability to influence and maintain that course may have become easier. Technological lock-in or system inertia is quite likely to be a topic which experts and analysts will write about for centuries to come. While its elimination may not be a goal, improved understanding of its salient features may go a long way in understanding socio-technical transitions.

Lock-in brings stability to systems as discussed earlier, so while the stability may be desirable to society as a whole, what may be more desirable to society as a whole is if (a) we can prevent early lock-in to sub-optimal technological configurations (and social behavioural patterns) that have negative social, environmental and system wide negative impacts and facilitate lock-in to a more benign system, or (b) given the uncertainty and gaps in our knowledge of future technologies, technological systems and their impacts, to gradually transition (facilitating lock-in) not toward any particular system of
technologies but toward a system architecture that is more open for a range of technological systems to plug-into in a distributed fashion. While we tend to spend most of our resources and energy searching and debating the former with proponents on all sides of the debate on their preferred technological configurations (i.e. including hydrogen systems), considerably less effort or discussion is seen on the benefits of guiding socio-technical change to a more open and flexible system architecture (in light of knowledge gaps and uncertainty of the future); neither option is trivial by any means, and as their comparison and analysis is beyond the scope of this paper it warrants a separate and more focused attention.

In the next section we turn to the literature on modelling of technical change in search of insights and building blocks for the discussion on socio-technical change.

4.3.3 Modelling Technological Change

4.3.3.1 Energy-Economy Models

Some valuable lessons may also be learned from the literature on modeling technological change in energy-economy models. Such models are used by governments and international agencies to understand the interaction of energy systems and the economy, as well as for decision making on future energy technologies. As such an entire literature has evolved around technical change and energy-economy models. Over the past decade a growing number of experts (Azar & Dowlatabadi, 1999; Grubb, Kohler et al., 2002; Grubler & Gritsevskii, 1997; Grubler & Messner, 1998; Grubler, Nakicenovic et al.,
1999) have criticized energy-economy models (E2 models) as well as E3 models\textsuperscript{73} for specifying technological change as an exogenous\textsuperscript{74} parameter, and argue that there is strong evidence that technological change is induced by a variety of factors such as market circumstances, expectations and policies. The specification of technical change as an autonomous process renders it insensitive to policy options or other socio-economic variables existing within the socio-technical regime and landscape.

When exogenous technology dynamics are introduced the optimal choice is to wait until the technology becomes competitive sometime in the future. (Grubler & Messner, 1998) call this an expectation of "technology falling from heaven". They further add that when new technology is taken up later, technological learning occurs later and therefore the technology maturation occurs later. As a result the positive effects of learning also materialize later. Although they acknowledge the mathematical and computational complexities of endogenizing technical change within E2/E3 models, first attempts to endogenize technological change and uncertainty (given the available computational power), points to a common conclusion: that, it is important to invest early in technology R&D, to learn through technological demonstration and niche markets and to continuously support the investment in these activities over a period of time\textsuperscript{75}.

\textsuperscript{73} E3 models - energy-economy-environment models.
\textsuperscript{74} This refers to the fixed or autonomous assumptions regarding the improvement of efficiency and declining cost for specific technologies over time.
\textsuperscript{75} It should be pointed out that failures in the past from stop-and-go operations in the R&D such as the massive technology crash programs of the multi-billion dollar U.S. Synthetic Fuel Programme as well as the stop-and-go production schedules of the Lockheed Tri-Star aircraft production, illustrate that technological learning and cost-reductions are not always proportional to scale of effort or the sum of its parts. According to (Grubler 1998), this can result in 'negative learning' or 'forgetting by not doing'.
Others have argued that endogeneous technological change can be captured through empirical research on consumer behaviour and consumer preference for technologies, in hybrid energy-economy models (Rivers & Jaccard, 2006). Hybrid models claim to offer the behavioural realism and macro-economic feedbacks that are lacking in the bottom-up energy-economy models and the technological explicitness missing in top-down energy-economy models. The technology explicitness refers to vehicle and building stocks, heating equipment, pumps etc., in the energy system and the behavioural realism refers to the modelling of consumer choice of technologies. While the modelling of consumer preferences is for technologies presently within the regime and potentially those still in niches, the focus is on consumer choice for individual technologies. Thus the technical change being modelled in energy-economy models is not about transformation of the socio-technical system but at most of incremental change. We will explore the question of technology choice and socio-technical transitions further in section 4.4.

(Audus, 2000) also is critical of the top-down energy-economy models that assume autonomous improvements in efficiency and costs over time and thus predicting “more of the same” technologies in the future. In addition, for all energy-economy models, he cautions against the input data bias in the models from advocates of particular technologies, regarding their performance. Furthermore he suggests that more attention be paid to less established technologies and the performance of all technologies be characterized based on a more balanced set of criteria (i.e. external costs, normalization of performance data, location of energy technology and end-user, siting constraints etc). While his goal is to improve the technology modelling process in energy-economy
models, his aim is to increase the confidence level for projections of technology deployment and performance. Thus this analysis also has a strong emphasis on technology in guiding socio-technical change.

4.3.3.2 Modelling and Scenario Analysis of Hydrogen Futures

An emerging sub-literature within the hydrogen futures literature is on the modeling of future hydrogen energy systems and economies. In a review of this literature (Joffe & Strachan, 2007) discuss a number of challenges associated with modelling of hydrogen economies, such as (a) modelling the competition for primary energy resources with other parts of the energy system (b) modeling the inherently spatial nature of hydrogen infrastructure development and (c) the level of technical detail required to appropriately represent the various hydrogen pathways. They also suggest institutional drivers, and behavioral change and attitudes towards risk as additional factors that may be important for modeling hydrogen economies.

A number of approaches to hydrogen modeling have been developed worldwide in response to some of these challenges. (Joffe & Strachan, 2007) group these hydrogen modeling approaches into optimization (least cost) and non-optimization models (scenario based). The optimization models for hydrogen are generally based on the popular bottom-up MARKAL (MARKet ALlocation) model. The scenario based models differ from the energy-economy models such as MARKAL as they do not focus on cost-

\[76\] The Intergovernmental Panel on Climate Change (IPCC) describes scenarios as “images of the future” (Nakicenovic, N, Alcamo et al., 2000) which are neither predictions nor forecasts, but an alternative image of how the future might unfold, while (Swart, Raskin et al., 2004) describe integrated scenarios as “coherent and plausible stories, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems”.
optimality between the different resource options and pathways. For instance the THESIS (Tyndall Hydrogen Energy Scenario Investigation Suite) Model explores the implications of GHG emissions of different hydrogen pathways and the HITES - Hydrogen Infrastructure Techno-Economic Spatial focuses on the spatial representation of the hydrogen infrastructure such as hydrogen distribution, hydrogen storage and compression requirements etc. The review suggests that each of the hydrogen models have their own strengths and weaknesses and ability to properly represent resource competition, energy system and economy interactions, spatial modeling of hydrogen infrastructures, temporal modeling of energy storage etc.

Not surprisingly all of the modelling approaches including the models based on hydrogen scenarios have a strong emphasis on the various technological dimensions of the hydrogen futures – which are essentially normative visions in favour of a particular technology or technology combination. While technology is clearly an important component of our future, the perspective taken here is that it does not drive the future; neither is it realistic to represent it as an exogenous parameter as in the top-down energy-economy models. While endogeneous technological modelling in energy-economy models is clearly an improvement, a further improvement would be to consider it as endogenous to social and economic change. This is consistent with (Berkhout, Frans, Hertina et al., 2002) who also consider technology as being shaped by factors such as markets, regulatory processes, policy and cultural factors. In other words it has a complex relationship with a multitude of factors in the socio-technical regime. (Berkhout, Frans, Hertina et al., 2002) also suggest that while some aspects of social change may be
modelled (i.e. demographic trends) others are more difficult or not tractable to modelling at all.

Moving beyond modelling and to a much higher level, the question then becomes if there is an alternative to choosing specific technologies (or set of related technologies) in order to guide socio-economic and socio-technical change or, as a corollary to the above, if we can decide on the type of socio-technical changes we would desire and the future we would like to live in and allow that decision to guide the choice of compatible technologies. We will return to this question more explicitly in section 4.4.1.

4.3.3.3 Energy Technologies and Scenario Analysis

In the context of socio-economic futures in climate change impact assessment (Berkhout, Frans, Hertina et al., 2002) recommend scenario approaches that combine participation, transparency and flexibility in a systematic process for their exploration. While the energy scenarios from the IIASA-WEC\textsuperscript{77} and IPPC scenario data base\textsuperscript{78}, is not a result of a public and stakeholder participatory processes, the assessment of a wide range of future energy technologies and energy scenarios by (Nakicenovic, Nebojsa & Riahi, 2001) suggest some important insights about the deployment of future energy technologies. Their analysis reveals how different development paths favour particular technologies, and recommend that energy policy should facilitate "research, development and deployment portfolios with different technologies" as a hedge against the uncertainties described in the scenarios. However, they venture to identify efficiency improvements,

\textsuperscript{77} International Institute for Applied Systems Analysis – World Energy Council
\textsuperscript{78} The IIASA-WEC and the IPCC scenarios are two of the most widely reviewed and analyzed large scale scenario studies conducted, to date.
decarbonisation, clean and zero carbon energy carriers, as robust generic energy sector technologies. The importance of hydrogen and fuel cells was identified in reference to electricity generation (stationary power), but not in the transport sector. While combined-cycle gas turbines (CCGT) were regarded as the most robust single energy technology across all scenarios considered (during the 1st half of this century), fuel cells, photovoltaic cells and nuclear energy were considered most robust in the long-term (2nd half of this century).

The point above is not about the specific energy technologies that were regarded as robust in the 1st or 2nd half of this century, but the fact that a scenario based approach was used in order to capture some of the inherent uncertainty of the future. While scenario analysis is one of the few methods available for assessing alternative developments, (Nakicenovic, Nebojsa & Riahi, 2001) warn that surprises and extreme events are often situated outside the envelope of future developments encompassed by scenarios in the literature. Thus they caution against the use of single “best guess” scenarios and against confusing actual future developments which are unpredictable, with any one scenario in the literature. The recommendation that follows therefore is not to choose any particular technology, but instead a diverse portfolio of technologies. We will expand on the implication of this point to the discussion on socio-technical change in the next section.

4.4 Discussion

This section will utilize the concepts, insights and building blocks that emerged from the earlier sections to discuss socio-technical change along 3 temporal dimensions: past
policy experience, present guidance for a hydrogen transition and some thoughts on
guidance for future transitions.

4.4.1 Past Energy and Technology Policy

Some important insights may be obtained about future transitions, by analyzing past
developments in technology and technology policy. Examining a number of aspects of
energy systems (from energy conversions, resources, substitutions) and the long-range
forecasts and predictions made by eminent innovators and leading experts of their time
(Smil, 2000) paints an embarrassing image of how the latter “have missed every
important shift of the past 2 generations” (Smil, 2000). These misses range from OPEC’s
unexpected rise in the sixties, the quintupling and subsequent quadrupling of oil prices in
the seventies\footnote{The Shell Group, that utilized a scenario based approach, were the only ones to have anticipated the rise in oil prices of the seventies.}, the collapse of the oversold promise of nuclear power, as well as the
overestimation of the potential for new energy conversions from synthetic fuels, wind,
solar, hydrogen, fuel cells, electric-vehicles (EV), while underestimating the cumulative
contribution of energy conservation post oil-crisis. Based on such a retrospective analysis
he cautions that new embarrassments and new misses lie ahead and that “we will be
repeatedly shocked by utterly unanticipated turns of events”. What Smil is cautioning
against is the dangers of forecasting as a tool for policy.

It is interesting to note that the confusion in the 1970s and 1980s in the energy regimes of
transportation, energy production and energy end-use, their inability to anticipate OPEC’s
rise (activities in the landscape level) as well as the failure of the new energy conversions
(niche technologies), fits within the MLP model discussed earlier. The success or failures
of such activities viewed according to the MLP model depend on the ability of the various ‘ongoing processes’ to link-up and align themselves with each other (Geels, Frank W., 2004; Rip & Kemp, 1998).

Highlighting the limitations of predictive forecasting (Robinson, J.B., 1988; Robinson, John B, 1992) argues for a ‘backcasting’ approach which works backwards from scenarios defined in terms of their desirability. The dominant approach to energy and technology policy in the past has been based on predictions on the most likely future, with absolutely no consideration given to the question of choosing a desirable one (Robinson, J.B., 1988, 2003). However, if we are able to identify a desirable direction for a transition, then perhaps a deeper understanding of the dynamics of socio-technical transitions might go some way in aiding this process. While the technological modelling literature suggests the difficulties of picking winning technologies of the future and thus the importance of diversifying the portfolio of technologies, making choices about a desirable future is still consistent with that suggestion. This is so because, choosing a desirable future is not the same as picking a particular technology (as the decisions are made at entirely different conceptual levels). As such, the concept of choice is far more complex than is often represented in conventional scientific discourse and policy circles. What may be desirable is not necessarily a technology or a set of technologies, but a way of being or a future with certain characteristics. If the choice is made at that level, then over time we may be able to influence the rules and grammar of the ST-regime, and perhaps indirectly over the long-term even some of the deeper cultural values, beliefs and views of the ST-landscape.
While this process may take time, the new rules of the ST-regime (based on exercising choice) may provide the opportunity for innovations within the niche that are compatible with the emerging paradigm, to make the transition into the ST-regime. This would further enable these niche technologies to co-evolve and develop inter-dependencies with other compatible technologies and systems, thus re-enforcing the original choices made (at the regime and possibly landscape level) and initiating a possible transition. While this may be the best-case scenario, assuming little to no interference from the incumbent regime (sailing-ship type effects) or unfavourable landscape developments outside of the control of regime actors (i.e. war, natural disasters, economic collapse), such a possibility would increase our chances of guiding a transition than if we relied on predicting the most likely future or if we made choices at the level of technologies.

4.4.2 Current Guidance for a Hydrogen Transition

In spite of the theoretical contributions from STS, the introduction of the MLP and recommendations and insights offered by those who analyzed past technology expectations as well as inter-temporal, inter-spatial and inter-sectoral diffusion processes, a number of analyses that favour a transition to a hydrogen future continue to adopt simplistic models of technological change and transition.

By looking at nine different scenarios which differ only by fuel cell performance and progress ratios for cost reduction (Tsuchiya & Kobayashi, 2004) conclude that fuel cell costs (PEMFC for automobiles) will drop to that of the ICE if mass produced. While this

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80 The progress ratio or learning rate is the decline in cost for every doubling of production (capacity). This parameter is often used in economics to describe the ‘learning curve effect’.
conclusion is not surprising\textsuperscript{81}, it says nothing about the differences in the fuel cell technology characteristics (among the different fuel cell types), added functionalities (if any), application domains and markets, public desirability and perception, or the infrastructural, fuel production and storage challenges on the supply side. Such one-dimensional analyses of cost reduction for fuel cells do not provide any significant input (or impetus) into the adoption potential or desirability of future fuel cell and hydrogen based technological systems or of such a future.

By drawing parallels between the internet and the possibility of future distributed hydrogen energy infrastructures (Clark, Rifkin et al., 2005) argue for a transition to a hydrogen based energy system. In a separate article the same authors make comparisons with the reduction in size of mobile phones (from brief-case size to shoe box size and presently wallet size) and their rapid diffusion (Clark & Rifkin, 2006) and suggest that the diffusion of hydrogen energy systems will follow a parallel path. The authors go on to describing the hydrogen economy as “a non-political movement supported by science and technology that the public wants without any universal vote or election.” Every technology is likely to have some feature in common with another, but based on the insights that emerged from the TTDM literature and from past mistakes the dynamics of technology diffusion and transition are clearly far more complex. While analyzing the effects of policy instruments in the residential sector (thermal insulation of new homes) (Jaffe & Stavins, 1995) quite modestly and accurately state that “the results could well be different for other technologies” and that they do not expect other applications to be simple extensions of their application as “The building sector is by no means typical of

\textsuperscript{81} Since this techno-economic analysis and conclusion will hold true for any technology still in R&D.
the broader economy”. Thus linear and one-dimensional analogies commit the fallacy of ceteris paribus⁸² and say little about the differences of technologies, how they might be consistent with a desirable future, the different transition contexts or challenges and policy implications that would be relevant to the public and policymaker.

In an attempt to make recommendations to the policymaker and the investment community regarding the transition to a hydrogen economy, (Zhao & Melaina, 2006) make a somewhat more appropriate technological comparison by attempting to draw insights from the experience of the Alternative Fuel Vehicle programs in the USA and China. However, these programs have only been in effect for about 15 years in USA and less than a decade in China. First, given that large scale technological transitions take between 5-10 decades (Grubler, Nakicenovic et al., 1999), looking back only 10-15 years may be insufficient to draw significant policy insights for a transition to a hydrogen economy. Secondly, given Berkhout et al.’s differentiated transition contexts (Berkhout, Frans, Smith et al., 2004), the transition to a hydrogen economy may be characterized more as a ‘purposive transition’ than the ‘endogenous renewal’ type transition for the AFVs⁸³. As such, care must be taken in extrapolating the insights from one context to another. And finally, given that the analysis of (Zhao & Melaina, 2006) was restricted to automobiles only, their insights are unable to inform the policymaker about the characteristics and dynamics of the other markets and end-use applications for hydrogen and fuel cells (see Table 4-1).

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⁸² This Latin term used occasionally in economics refers to the assumption of “all else being equal.”
⁸³ This is so because many of the proponents of a hydrogen energy future are often actors outside the regime and are trying to cause deliberate change.
Each of these analyses has clearly been about choosing technologies rather than a desirable future way of being. However, if for some reason we can only make choices at the level of the technologies, it would still be better informed if (a) more appropriate technological comparisons are made (not assuming all else is equal) (b) the different applications of hydrogen and fuel cells are considered in light of their different socio-economic and technical characteristics and (c) the appropriate transition contexts are considered, before making recommendations for future transitions to the policymaker.

4.4.3 Some thoughts on guiding Socio-Technical Change

As alluded to before, the literature on technology diffusion, modelling technical change, strategic niche management and transition management often refer to the importance of protecting novel technologies within technological or market niches in order to facilitate their further development and eventual diffusion into the market place. The expectation is that the technologies will eventually link-up with critical events in the ST-regime and landscape.

However, critics of transition management argue that managing transitions is a contradiction in terms, given that far simple processes have proven impossible to manage (Elzen, Geels et al., 2004). The underestimation in the requirement of a receptive ST-regime in promoting innovative technologies, has also been given as a weakness in past policy-making (Shackley, Simon & Green, 2007). This is also consistent with the view of (Joerges, 1988) who in the context of LTS questioned the ability of regime actors for reflexive action due to its complexity and their ability to form a complete picture of its inner workings. As such many technologies in niches do not breakout into regular
markets. Although niche creation and its management may be accomplished in some cases, the process of managing the transition from niche level to the mainstream ST-regime is often more complex than is recognized.

The differentiated transition contexts introduced by (Berkhout, Frans, Smith et al., 2004) also add more texture to our understanding of transitions as it emphasizes the importance of recognizing that transitions are essentially a result of a mixture of intended (this refers to the point about choice made earlier) and unintended outcomes of historical processes, and that while activities in the niche level may link up and converge with landscape developments to create transitions (in a bottom-up fashion), transitions may also occur due to downward pressure from the landscape alone (top-down). As such Berkhout et al. are critical of the niche-regime transition as being too reliant on solutions grown in niches.

This point also lends support to the proposition made here which encourages thinking about a future and constructing it without relying entirely on ‘conceptual crutches’ that are technology reliant and without being limited to guiding their transition from the niche to regime. Alternatively, we may seek guidance and think about future transitions in terms of questions and choices that operate at a level that is above the level where we make choices between technologies; for instance, how we may want to balance urban density over urban sprawl (given the anticipated rise in urban population in the coming decades), if there should be better public transportation and increased support for alternative modes of transportation, what are the energy services we would like and what

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84 Perhaps there is a need to point out the obvious that the numerous ‘S’ shaped logistic curves as well as learning curves that are analyzed and discussed in the literature are of those lucky few that made the transition from their niches to the ST-regime.
standards should there be about its quality, convenience, environmental performance etc., how much do we care about stabilizing atmospheric concentrations of GHGs (at or below 550 ppm), how to adapt to the increasing threat of water scarcity worldwide, the kind of world we would like to leave behind for our grand-children etc., or some combination of them. Many of these higher level questions will affect the choices we make for the future, but they do so in a top-down manner – ST-landscape to regime and niche. The process of articulating these ideas help create, recreate and reshape different aspects of the landscape or regime levels.

As mentioned earlier the MLP suggests that the ST-landscape forms gradients for action making it easier for some socio-technical developments to move in particular directions over others. If this is indeed true then, niche-to-regime transitions may face unforeseeable or perhaps insurmountable barriers if they are incompatible with the gradients of the landscape. Perhaps this might explain the failure of some niche technologies and the success of some technologies and systems (presently within ST-regimes) which are incompatible with a vision of a future not yet embedded within the landscape. All this provides further support to a top-down approach the emergent result of which would be the formation of policy and relevant institutional frameworks enabling particular technologies and technology combinations, compatible with the vision of the articulated future, to link-up and align with these ‘ongoing processes’ (Geels, Frank W., 2004; Rip & Kemp, 1998). Ultimately certain niche technologies will make the transition to the ST-regime, as with the bottom-up approach, but for entirely different reasons.
The top-down process for a particular nation or jurisdiction may be facilitated by a participatory process where the public and stakeholders, based on the collective expectations, create a coherent vision of the future. (Smith, Stirling et al., 2005) discuss the importance of visions and expectations of the future as being a prerequisite for having the power to affect change. However, they point out that the process of constructing a coherent vision of the future is far from unproblematic and that problem framing, coordination of responses and agreeing on how to use available resources are not straightforward. Different actors may share different perspectives and visions of the future, therefore what is essential to this process is that it is (a) participatory (b) involves a diverse set of stakeholders (c) for exploring a set of alternative futures. This is one way to recognize the different perspectives engage in a debate and facilitate learning. The suggestion made here is that such a discussion should start with higher level questions that operate at the landscape or regime level (without first having to make choices about technologies) and then move down as necessary to the level of policy and technology variants. In this manner we may attempt to construct the future we desire, than simply stumbling along a path where choices are being made, for instance, based on the most ‘cost-effective’ technology (the notion of cost-effectiveness operational in today’s decision making may not only be very limited but also directly conflict with our idea of a desirable future).

(Robinson, J.B., 2003) suggests how through the process of engaging with stakeholders the desired future becomes an emergent property of the process (second generation of backcasting) of "structured conversations about future options, consequences and tradeoffs, that combine expert understanding with the knowledge, values, and preferences of citizens and
stakeholders". Therefore, rather than the 'desired future' being determined in advance (as it often is when individuals or groups (lay and expert) with similar interests and views align themselves with each other) it becomes the product of a social learning process, between experts and ordinary citizens.

Unfortunately however, in reality, visions and expectations expressed of desirable futures are rarely a result of such social learning exercises, which are balanced across a representative selection of public, stakeholders and experts. Instead, they emerge more commonly as “...'bids' that are deployed by actors in processes of coalition-formation and coordination” (Berkhout, Frans, 2006). These bids also tend to be bids for particular technologies or technological configurations, implying futures that are 'technology-driven'. This may be a result of an implicit bias toward the 'technology' component of a socio-technical system and the importance given to its apriori selection in guiding socio-technical change.

The above insights on managing and guiding transitions would be of utmost importance for actors presently in the ST-regime (ICE automakers, petroleum producers and policymakers) and arguably more so for those outside it (i.e. promoters of a hydrogen economy or solar-electric economy). While these insights may not provide direct guidance on how to create a transition step-by-step, it provides an alternative mode of thought and perhaps approach, which may help in understanding the complexity and challenges of the transition process.
4.5 Conclusions

The hydrogen futures literature was used as a means for discussing concepts from the theoretical literature on transitions, the empirical literature on the diffusion of infrastructures and clusters, and the technology modelling literatures. It was demonstrated that important synergies exist between these literatures and that the exploration of which provides guidance for new ways of thinking about future transitions.

If the goal is a pervasive hydrogen economy then three recommendations that emerge are:

1. To explicitly consider the different diffusion barriers for the different fuel cells on the demand side and to acknowledge the heterogeneous nature of a hydrogen economy when making policy.

2. To recognize the complexity of the technology diffusion and transition process and not to commit the fallacy of 'ceteris paribus' when making technology comparisons and policy recommendations for future transitions; that transition pathways as well as their sustainability are strongly dependant on the conditions prevailing within the regional socio-technical landscapes, regimes and niches.

3. In the transport sector, in addition to cost-reductions, Fuel Cell Vehicles may need to demonstrate sustainability benefits in order to improve their competitive advantage and public acceptance.

However, even the above suggestions may be simplistic, considering the complexities involved in socio-technical transitions. To improve this understanding, the main insights
that emerge from the combined analysis of technology transitions, diffusion and modelling literatures, and their implications are discussed below:

1. The diffusion of infrastructures and technology clusters over the past 200 years reveals a window of opportunity at the present time for another technological transition, based in the saturation of the existing technological cluster.

2. The technology modelling literature recommended early investment in a diverse portfolio of technologies without suggesting any clear direction for a transition, due to the unpredictability of future developments.

3. Although the multi-level-perspective of technological transitions suggest that technologies within niches can breakout into mainstream markets and diffuse when they link-up with developments in the ST-landscape (or ST-regime), presently there is no theory of how to go about forging such links.

4. Our historical record shows that technological change rarely took the direction predicted by experts or proponents of new technologies, leading us to failed forecasts and policies.

If a window of opportunity indeed exists, then the question becomes how can we guide a transition and what can we learn from our past? Given the unpredictability of the future acknowledged by the technology modeling literature, it is not surprising that predictive forecasts in the past failed. In addition, predictive forecasts operate at the level of the individual technologies or groups of technologies. As shown through the multi-level-perspective, in addition to technologies there are the rules and practices (the grammar)
that provide stability to the ST-regime. Similarly at the landscape level, there exist the deeper cultural beliefs, values etc.

Given that technologies are but one dimension of the larger socio-technical system, choosing technologies for our future may be like trying to get the ‘tail to wag the dog’. It may be reasonable to conjecture that at the most basic level, in terms of energy, what the public may really care about is energy services which are affordable and high quality energy carriers (Nakicenovic, Nebojsa, Grübler et al., 1998); and in terms of a future, qualities such as a clean environment and peace where people may live and work freely. To cast it differently, few among the public are likely to insist that in the future their automobile should be powered by an internal combustion engine running on gasoline/diesel, or that any set of technologies alone may characterize a desirable world.

Thus an alternative way to think about socio-technical change and transitions may not be in terms of the currency of technologies, but in terms of a desired future and its more broad ranging characteristics. If it is possible for such a choice or vision to emerge through a collective social-learning process (Robinson, J.B., 2003) then perhaps this can gradually influence the values, beliefs and cultural aspects of the ST-landscape. This in turn could affect the operation of the various institutions that govern the rules of the ST-regime, which would then enable technologies within the ST-niche that have a greater compatibility with the original choice to emerge and become part of the ST-regime. This may further enable the niche technologies to co-evolve and develop inter-dependencies with other compatible technologies and systems which are in other niches or which are already in the ST-regime. Thus the technological changes and transition is more likely to
be compatible with the broader desired future, in affecting an overall socio-technical transition. While this may be the best-case scenario, assuming little to no interference from the incumbent regime (sailing-ship type effects that are successful) or unfavourable landscape developments outside of the control of regime actors (i.e. war, natural disasters), such a possibility would increase our chances of guiding a socio-technical transition than by relying on predicting the future or by making choices at the level of technologies.

As it stands, at the global level the 'adaptive capacity' (Berkhout, Frans, Smith et al., 2004) of the incumbent fossil based regime seems sufficient in the short-term. However, in addition to the observation noted earlier about a presently saturating technology cluster, landscape developments such as climate change and geo-political tensions in the fossil rich middle-east, as well as small but growing public acceptance of alternative energy technologies at the regime level, point to opportunities in the future for particular niche based technologies to link-up, relieve tensions and create alternative trajectories for regime development. The success or failure of these developments will depend on how the goals and desired futures are articulated, and the eventual outcome is unlikely to be steered by any one group of actors, but by the collective action of numerous interacting groups that make up the social fabric of technology.
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5 Concluding Chapter

5.1 Introduction

The goal of this chapter is to provide a final discussion and overall conclusion for the dissertation, focusing on the combined results of all manuscripts. As such, no summaries or conclusions from each manuscript will be provided explicitly. The reader is referred to the last section of each manuscript for that purpose. If I may use the terminology of the Multi-Level Perspective in a slightly different context, this chapter may be regarded as a discussion occurring at the landscape level, if each manuscript may be considered as a discussion at the regime level.

Before highlighting the main conclusions and insights from the earlier manuscripts, we will digress momentarily in order to explore two important questions regarding sustainable transport systems and hydrogen energy futures for BC. The two questions which are identified below were largely outside the scope and objectives of each of the manuscripts, but nevertheless given their relevance and significance to the overall discussion we will discuss them in sections 5.2 and 5.3.

In chapter 2 the sustainability assessment was based on a real life demonstration project in BC, which is largely a demonstration of the collective technology expertise within BC related to hydrogen and fuel cells at this point in time. One could argue that this collection of particular technologies may not necessarily provide or contain the main elements of a sustainable transport system. Besides, the BC Hydrogen Highway project
clearly has a strong bias in favour of hydrogen and fuel cell systems. Conceivably the concept of sustainable transportation may be broader than the collection of any particular set of technologies. Therefore, moving beyond specific transportation technologies, section 5.2 will show how one may think about the broader question of sustainable transport systems and what the main considerations might be for a particular region. This in turn would potentially inform the sustainability assessment of regional transport systems.

Secondly, even if we limit ourselves to the discussion of hydrogen and fuel cell systems in BC, the Hydrogen Highway project did not actually map out the inherent uncertainty of hydrogen energy futures for the province. Given the unique set of primary energy sources available in BC, different hydrogen production pathways and fuel cell types, their different combinations may give rise to a variety of different possibilities for the future. However, the different future possibilities are not simply a direct function of particular permutations or combinations of technologies, but more importantly of the underlying driving forces within the socio-technical landscape and socio-technical regimes. In other words, given the variety of possible driving forces such as public perception and their values, global and regional market and resource dynamics, geo-politics etc., a variety of different plausible scenarios with different technology dynamics may emerge, even within the confines of hydrogen energy futures in BC. Given this apparent gap in the discussion surrounding hydrogen and fuel cells in the province of BC, section 5.3 will attempt to capture some of the future uncertainty of hydrogen futures through an exploration of the plausible scenarios for the province.
In section 5.4 we will revert to the manuscript chapters and discuss the relationship between them. This will be followed by the main conclusions from the dissertation which will be outlined and discussed in section 5.5. Section 5.6 will be a discussion on the significance of this research to the field of study followed by a discussion on the potential applications of the research findings in section 5.7. Finally, section 5.8 will offer some comments on future research and close with a final word.

5.2 Sustainable Transportation and Sustainability Assessment

The BC Hydrogen Highway project discussed in Ch2 was analyzed for some key metrics in order to gain insights about its sustainability. However, a much higher level question is, irrespective of any particular technologies, what would be the main considerations in designing such a sustainable transportation system and what would it look like?

Transportation is a service that is essential for the proper functioning of any given jurisdiction or region. While transportation services and demands are heterogeneous across the globe, the discussion here will focus primarily on a system such as the one prevalent in Vancouver in a developed country. Also transportation systems may be based on land, sea or air. For the sake of simplicity the discussion will focus primarily on land based transport systems.85

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85 In theory, the design for a sustainable transportation system for a region should cover land, marine and air based transportation. Unfortunately the regulatory bodies and authorities for each of these categories all have different mandates and have vastly different stakeholder groups.
Land based transportation service may be split into three fundamental components: motorized private transportation, motorized public transportation and non-motorized transportation, each containing a variety of different modes. Table 5-1 below provides a list of transport modes that fall within each of these categories.

<table>
<thead>
<tr>
<th>Transportation Service</th>
<th>Transport Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorized Private Transport</td>
<td>Privately Owned Automobiles, Trucks, Motorized Boats, Motor-cycles, etc.</td>
</tr>
<tr>
<td>Motorized Public Transport</td>
<td>Bus, Trolleys, Trains, Rapid Transit Systems, Coach-line buses(^{86}) (i.e. Greyhound) etc.</td>
</tr>
<tr>
<td>Non-motorized Transport</td>
<td>Biking, Walking, Roller-blading, Skate-boarding, etc.</td>
</tr>
</tbody>
</table>

Table 5-1: Components of Land based Transport Systems.

A sustainable transportation system may be defined as one that provides its citizens the ability to use the above transport modes in a manner that is convenient and accessible (social dimension), affordable (economic dimension) and with the least possible emissions and resource use (environmental dimension). In this context it would be desirable to see (a) firstly, a gradual shift away from motorized (private or public) to non-motorized modes of transport (b) and secondly, a shift away from motorized private to motorized public transport, in that order. As one would expect, meeting all these criteria simultaneously is not a trivial task. Assuming this to be the guiding vision, we discuss below a variety of different challenges that need to be addressed as we consider the design of sustainable transport systems.

\(^{86}\) Coachlines although technically not publicly owned are put in this category since in the context of sustainable transportation they provide a better alternative than if personal motorized vehicles were used.
One key challenge is that patterns of transportation are strongly linked with patterns of land-use. This is one of the key arguments behind Smart Growth (SmartGrowthBC, 2007). Given that transportation is responsible for a significant share of total emissions (25% CO2 emissions in Vancouver by cars only), a key sustainability objective should be to reduce transportation’s share of emissions. The idea here is that if a neighbourhood or community is designed with a mixture of homes, retail, business and recreational centres then its citizens are more likely to use one of the non-motorized means of transport, thereby reducing potential harmful emissions. Therefore, in designing sustainable transportation systems for the future, one would inevitably need to consider how new communities and neighbourhoods are planned.

A related concept is Ecodensity (City of Vancouver, 2007) which is based on the concept of Ecological Footprint (REF) and focuses on how much land we need to support our lifestyles. The premise here is that sustainable living means minimizing total land-use when building communities and the supporting infrastructure. As far as transportation is concerned Ecodensity suggests increasing public transit services, walking and cycling and reducing the number of cars on the road. Also it encourages reducing the distance between one’s home and workplace, thereby reducing total transportation activity and emissions. It should be noted that increased use of non-motorized transport and transit also has intangible benefits to the public such as increased exercise and improved health as a result.

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87 Green house gas emissions (i.e. CO2) are responsible for climate change impacts while SOx and NOx emissions are responsible for acid rain formation and impacting agriculture. NOx and VOC’s also contribute to the formation of ground level Ozone and PM is most directly formed through combustion of most carbonaceous fuels. Increased PM and ground level Ozone are associated with increased risk to human health.
From a life-cycle perspective reducing the number of cars per-capita would also lead to a reduction in the material and energy that goes into their manufacture. Encouraging membership in car co-operatives is also another way to reduce vehicles per capita and thus per-capita emissions.

Much inspiration for urban planning and sustainable transportation can be gained from the city of Curitiba in Brazil. Curitiba has been described by many as the best planned city in Brazil and model for sustainable development. While having about twice the population of Vancouver and despite having to deal with the challenges of rapid growth (population doubling in 30 years) the city’s planners and architects have improved the city’s quality of life not only through improvements in public transportation, but also through the increase of green space per capita, preservation of cultural heritage and a variety of environmental and social programs (ICLEI Local Governments for Sustainability, 2007). With regards to public transportation, Curitiba has one of the most sustainable transport systems that originated with a plan, the Curitiba Master Plan, in 1968. The plan resulted in a configuration which consisted of dedicated express lanes for buses, and these roads forming a star that converges around the city centre. Much attention was also devoted to the design of buses, bus-stops and travel-fare, with long buses in 3 sections, elevated tubes for easy loading/unloading, easy disabled access and single-fare system regardless of distance travelled. Each of these demonstrates the importance of going beyond just reducing emissions, and maximising convenience and user-friendly interface between technology and user.
The SmartGrowth and Ecodensity principles help reduce emissions and resource use by helping us re-think how we live and commute. In other words, this helps us in reducing our activity level. For a given activity level however, it would also be beneficial if we are able to reduce emissions per unit activity (i.e. grams CO2 per km driven). This is achieved by using technologies and fuels which are low on emissions. While particular technologies facilitate the use of a given fuel, it is ultimately the carbon and sulphur content in fuels that are responsible for CO2, PM and SOx emissions and the temperature of combustion itself causing NOx emissions. Thus in order to get closer to the a sustainable transportation system one must also consider reducing the carbon content of the fuel and moving toward fuels with greater hydrogen to carbon ratio (i.e. from petroleum to natural gas) or to blends of ethanol or bio-fuels which can also reduce harmful emissions.

In this regard, it is crucial however to consider life-cycle emissions when evaluating bio-fuels. While it is often argued that the combustion of bio-fuels is carbon-neutral (since the plants once absorbed the emitted CO2 from the atmosphere) each case must be analyzed separately for total energy and emissions from the production of the crops converted to bio-fuels (this is the same argument earlier in Chapter 3 regarding upstream emissions from petroleum production). While bio-fuels in general may still emit less than their fossil fuel counterparts, in some cases the economic and environmental argument in favour of bio-fuels may be quite a bit weaker than initial perception, depending on the energy balance and emissions analysis. The ethanol production from corn in the USA has been described as one such example (Patzek, 2004).
Sustainable transportation also means that transportation must be affordable to the consumer. The challenge of balancing emissions versus costs of transportation fuels and technologies arises due to the fact that current economic models assign a near-zero if not zero price to the environment. Thus if we try to minimize cost (as defined today) to the consumer, given that most petroleum based fuels and technologies are the least cost-option, our transportation options converge on petroleum based solutions. Thus practices related to full price accounting (green accounting) or environmental accounting would need to be incorporated into our cost models to reflect true cost of a technology/fuel in order to approach sustainable transportation.

While petroleum and related technologies appear as least-cost options in most cases, given that regional economics may differ, due to the asymmetric distribution of resources and technologies different options to attain a sustainable transport system may emerge for different regions. For instance, since ethanol production was subsidized in Brazil in the 1970's Brazil was able to develop the technology reduce production costs (due to learning curve effects) and become a world leader in ethanol production. Today Brazil obtains over 30% of its automobile fuels from ethanol, thus significantly reducing its emissions (Lovins, A., 2005). Thus this points to the importance of evaluating regional opportunities to produce more benign fuels where possible and the importance of investing in fuels and technologies, which based on a life cycle analysis emerge as solutions for reducing total transportation emissions (both upstream and downstream). Such a strategy would also facilitate a transition to a more sustainable transportation system.
5.2.1 Implications for Policy

As alluded to above through the concepts of SmartGrowth and Ecodensity, given that there is a strong link between transportation and land-use planning and community development, sustainable transportation may not be discussed in isolation without consideration to how we plan and build communities. Provincial and municipal governing bodies need to make changes to outdated regulation (i.e. zoning, by-laws, codes etc.) create incentives (i.e. insurance, taxation) for the public and commercial entities and remove disincentives that discourage resource optimization and go against the vision of sustainable transportation and sustainable living. A number of different policy alternatives may be pursued in this regard by both levels of the government in BC.

Public Engagement

Already the city has engaged through the ‘CityPlan’ initiative and the ‘Community Visions’ program to engage with the citizens to ask them about their vision of how they would like to see Vancouver and their neighbourhoods develop over the next 20 years (City of Vancouver, 2007). The people have voiced their desire for denser and affordable housing and mixed neighbourhoods and identified 17 neighbourhoods they would like to see developed. This provides a good starting point for planning for land-use and developing sustainable transportation services.

Shifting from motorized to non-motorized transport modes

The most significant reduction in emissions can be achieved when communities are designed to obviate the need to use their personal motorized or public motorized transport
modes. The simplest way to achieve this is to encourage mixed use developments that provide residents with easy access to recreational facilities, neighbourhood parks and green spaces for children and families to enjoy, retail outlets etc. In doing so, particular attention to detail may be necessary to make walkways and bike-paths pedestrian and user-friendly. For instance, it is important to make the experience safe and enjoyable to those using it. For instance measures such as curb bulges at cross-walks reduce the time pedestrians have to be on the roads as well as increasing safety by pedestrians and drivers being able to see each other easily (City of Vancouver, 2007). Similarly the city may increase the number of pedestrian controlled traffic lights which empower those on non-motorized transport modes and allow them to reduce travel time; they also work as a disincentive to drivers on the road as it would increase their travel time (relatively speaking). However, by reducing the speed limit for cars and allowing buses special privileges on city road may provide further disincentives to personal motorized transport.

Another measure is to increase bike-ways in the city, which the City of Vancouver has already made a goal after seeing the benefits of it from many European cities. Other programs may further enhance this initiative such as innovative bike-share programs that cities like Vienna and Lyon have quite successfully implemented. Given their success in these cities, other cities worldwide are now considering implementation of similar programs.
Reducing the impact from Motorized Transport

London in an effort to reduce the city’s air-pollution and congestion has implemented a disincentive program based on a congestion charge over $15 (8 Pounds) to motorists entering a 13 sq. km zone in central London between 7am-7pm during weekdays. There are plans currently underway to increase this to almost $50 (25 Pounds) to further help shift motorists to taking alternative modes of transport. (It should be noted that the city is considering discounts to those driving more efficient vehicles.) While the effectiveness of this program needs to be studied, important lessons may be obtained from such social experiments when implementing in other countries with similar socio-economic conditions.

Car Co-operatives also help reduce the number of cars per capita, encourages multi-modal transport (as members generally use a combination of the car, bus, biking and walking for their transportation needs) and thus reduces overall emissions. Furthermore, the greater the membership of car co-ops the less that many fewer cars would need to be added to the market avoiding the energy and materials demand for their production as we had discussed in chapter 3. While members of car co-operatives generally save money as they only pay for the time used and distance travelled, to encourage further participation either government subsidies or tax benefits (city-wide free-parking for co-op cars) may be provided to further enhance its attractiveness. In Vancouver, a city of approximately 2 million there are presently about 3000 members in its Co-operative Auto Network (CAN). It should be noted that car co-ops generally work better in dense neighbourhoods than in low density areas, further supporting the case for density.
Another measure that would immediately have an impact in reducing car emissions is to move away from a flat-rate car insurance to a pay-per-km car insurance (City of Vancouver, 2007). The former penalizes those who drive less, providing no incentive to drive less. Arguably the biggest component of insurance is from accidents and the associated liabilities. Probabilistically speaking, if a car spends less time on the road, then all else being equal, its risk of getting into an accident is also reduced proportionally. This further supports the argument for pay-per-km car insurance.

**Investments in Sustainable Technologies**

As discussed earlier in the literature on endogenous modelling of technological change, the main recommendation was to invest early in technologies and to continuously support investment in these activities over a period of time. The Brazilian example noted above of continued investments in ethanol production over the decades is a clear success story in this regard. Similarly, in Curitiba the investments in their public transport infrastructure are also an example of investments that contribute toward sustainable transportation. Similarly governments may help reduce market barriers to other bio-fuels that reduce overall emissions and increase research and development support to technologies that show potential in reducing life-cycle emissions.

Finally to conclude the discussion of sustainable transportation systems, Table 5-2 provides possible metrics that may be used in monitoring progress toward sustainable transportation. Each of these emerges from the earlier discussion and while not
necessarily exhaustive may provide a reasonable starting point to assess sustainable transport systems. Clearly each of these would have direct impacts on other criteria such as CO2 emissions, SOx, NOx and PM emissions, resource use and ecological footprint, energy efficiency, water consumption, bio-diversity impacts, health of public, public safety, affordability, convenience and overall quality of life to name but a few. Thus the implementation of the relevant policy measures discussed above for a particular region would not only help improve on each of the criteria below but would allow it to benchmark the current state of their transport system and begin a process toward a more sustainable transportation system.

<table>
<thead>
<tr>
<th>Km of bike routes in the city</th>
<th>Car Co-operative membership per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green space per capita</td>
<td>fraction of mixed-used neighbourhoods area compared to total area of city</td>
</tr>
<tr>
<td>Number of vehicles per capita</td>
<td>Total passenger kilometres per bus (Bus rider ship)</td>
</tr>
<tr>
<td>Number of alternative fuelled vehicles per capita</td>
<td>Total automotive (petroleum) based km per vehicle class</td>
</tr>
</tbody>
</table>

Table 5-2: Possible metrics for monitoring progress toward Sustainable Transportation

5.3 Hydrogen Energy Scenarios for BC

As mentioned earlier, the focus of this section is to describe a number of plausible images of hydrogen futures based on the underlying driving forces within the socio-technical landscape, regime and niche (i.e. market and natural resource dynamics, geo-politics, international treaties, niche technologies etc.) of British Columbia. Depending on the timing and resulting combination of driving forces that may emerge in the future,
different scenarios may be conceivable. These scenarios help represent the uncertainties involved and the socio-economic, market, technological and political forces that may affect the diffusion rates of particular hydrogen and fuel cell technologies.

5.3.1 The Scenarios Approach

The scenario method was first introduced by Herman Kahn (Kahn & Wiener, 1967) as another method to probe the future. Kahn’s work on the scenario method was strongly influenced by his work at the American think-tanks RAND and the Hudson Institute during the 1950s and 1960s (Dreborg, 2004). In the private sector one of the early pioneers of the scenario method was the Royal Dutch Shell group of companies (Shell International, 2002). Under the leadership of Pierre Wack in the late 1960s, a team at Royal Dutch Shell corporation used scenario analysis as a tool to anticipate future possibilities (Wack, 1985a, 1985b). The team developed optimistic and pessimistic scenarios as part of their analyses. The pessimistic scenario was influenced by their hunch that there were signs of trouble in the world oil markets as world consumption was skyrocketing, US production was leveling off and the Middle Eastern nations were rapidly increasing their share of the world oil market (Lenssen & Flavin, 1996). The scenario approach enabled the company to become more sensitive to surprises and as a result they were able to respond more readily to the oil embargo of 1973.

Scenarios are descriptive conceptions of possible futures. The descriptions can range from being qualitative, quantitative or some combination of the two. Scenario analysis can help users to consider possibilities they had not conceived of before. According to Shell, “scenarios help us understand the limitations of our ‘mental maps’ of the world –
to think the unthinkable, anticipate the unknowable and utilize both to make better strategic decisions” (Shell International, 2001). The Intergovernmental Panel on Climate Change (IPCC) similarly describes scenarios as “images of the future”, that are neither predictions nor forecasts, but an alternative image of how the future might unfold (Nakicenovic, Alcamo et al. 2000). Perhaps the most important use of the scenario approach is that they can act as a crucial bridge between science and policy - scenarios can influence policy making by summarizing and synthesizing scientific knowledge in a form that can be used by policy makers to develop policies.

The BC Hydrogen Highway is a demonstration project and as such is a collection of a variety of hydrogen and fuel cell technologies at various stages of development. As mentioned in chapter 2, the goal of the organizers is to showcase these technologies at the 2010 winter Olympics in Whistler-Vancouver. A scenario based approach to scanning the future possibilities for hydrogen and fuel cell applications in BC was not an objective of the BC Hydrogen Highway project. These technologies and applications did not emerge from any analysis of the underlying technological, resource or socio-economic variables that could guide the direction of hydrogen futures in BC.

5.3.2 The Scenario Generation Process

The scenarios described below will consider the present resource, market and socio-economic conditions prevailing in BC and present three alternative and coherent narratives for hydrogen and fuel cell futures plausible for BC, independent of the Hydrogen Highway project or the particular technologies contained within it.
The scenarios may be characterized based on two important differences - the dominant primary energy source and dominant end-use application (representing the 2 ends of Figures 1-2 and 1-3). These are represented in 2-dimensions in Figure 5-1 below.

![Figure 5-1: Scenario space considered for BC.](image)

Given that a primary energy source (or a combination of sources) is absolutely essential for any given energy system and its carbon to hydrogen ratio is a key parameter of its carbon intensity and thus carbon emissions, it would make sense to distinguish scenarios based on their dominant primary energy source. Also, the form and particular technology characteristics of the end-use application (i.e. fuel cells for automotive power, fuel cells for portable electronics), would determine the type and form of secondary energy carrier (i.e. 99.99% pure hydrogen for cars, methanol cartridges for portable electronics) as well.
as its storage and distribution requirements. As such the intermediary production, energy conversion, storage and distribution are details of the energy systems which are a function of these 2 criteria (and axes of Figure 5-1) – primary energy source and end-use application.

The x-axis represents 3 different primary energy sources that could be dominant for hydrogen energy scenarios in BC, while the y-axis represents the 3 dominant end-use fuel cell applications. As shown in Figures 1-2 and Figure 1-3, a number of different primary energy sources exist that may be utilized for different hydrogen scenarios. However, for simplicity Hydroelectricity, Natural Gas and Coal were chosen here for the scenario generation as they represent the 3 primary energy sources that BC has large endowments of. As far as end-use applications, as described in Table 4-1, there are 3 main areas where hydrogen and fuel cell applications may diffuse into – transportation, stationary power and portable electronics. This is true for BC as well as for other regions.

Based on the 3 options in each axis of Figure 5-1 up to 9 different scenarios may be generated. However, not all of the scenarios that may be generated from the matrix in Figure 5-1 are expected to be technologically feasible or economically viable over the next two to three decades. The 3 scenarios chosen for discussion here are based on technology combinations that are most likely to be commercially viable by 2030 - the time frame of these scenarios. This likelihood is determined qualitatively by an analysis of the literature on each of these technology combinations. The three hydrogen energy scenarios for BC that emerge from this analysis are: Scenario-A - characterized by
natural gas and portable electronics; Scenario-B - characterized by natural gas and stationary power; scenario-C – characterized by coal and transportation.

It should be noted that in addition to the 9 possible scenarios in Figure 5-1, additional primary energy sources may be added to the x-axis, increasing the total number of scenarios further. However, based on the Shell experience with scenario analysis, it is more productive to focus on a small number of thought-provoking scenarios than numerous variants (Shell International, 2001). This further explains the choice of the 3 hydrogen and fuel cell scenarios here for BC in 2030.

While different scenarios may vary based on a variety of macro-economic factors (i.e. GDP, Inflation, population etc.), in order to focus on the uncertainties involved with the primary energy sources, hydrogen and fuel cell technologies and the underlying socio-economic drivers that can bring about their variation, no major changes due to demography and economic growth rates will be considered in the scenarios discussed below. As such they may be assumed to be consistent with the assumptions for the Techno-Vert (TV) scenario of the National Energy Board (National Energy Board, 2003). Table 5-3 below provides the assumptions used in the NEB-TV scenario for Canada.
Table 5-3: Macroeconomic Assumptions for National Energy Board Techno-Vert Scenario.

5.3.3 Scenario-A

Of the 3 main end-use technology application areas, fuel cells in portable electronics (low power applications - < 100 W) leads the way in terms of diffusing into regular markets and reaching the consumers in BC. This is supported by a number of technical and socio-economic factors such as (a) the small cost-differential (between full cell powered and battery powered portable power) (b) the added power requirements in personal communication devices, laptops, etc., due to the growing number of functionalities demanded by consumers (i.e. phone, camera, mp4 player, internet browser, personal digital assistant, e-mail) and the inability for battery power technology to keep up with the energy, power densities and short recharge times (c) and the lack of need for any infrastructure to support portable fuel cells and hence no infrastructure related costs or technical challenges.

This trend to fuel cell powered portable electronics is not only seen in BC but in North America, Europe and much of the rest of the world. As a result of economic
growth worldwide, increased personal disposable incomes and travel, more and more people demand portable electronics with multiple functionalities and long time frames between recharge. Volume production due to increasing demand reduces costs globally as well as in BC. If the above social, economic and technological driving forces combine simultaneously, it would create the conditions that would favour a scenario dominated by fuel cell powered portable electronics with methanol as the fuel.

Figure 5-2 shows how the demand for portable fuel cell powered electronics change over a period of about 25 years. The characteristic diffusion time\textsuperscript{88} is about 20 years. This 20 year timeframe would seem a reasonable estimate, given the diffusion timeframe of 5 years for computer DRAM technology (Victor, Heller et al., 2003) and a diffusion time frame of greater than 50 years for large scale energy systems (Grubler, Nakicenovic et al., 1999).

\textsuperscript{88} The time taken to go from 10\% to 90\% market share, or from 0-50\% market share.
The increased demand for methanol for Direct Methanol Fuel Cells (DMFC) used in the portable electronic devices further strengthens Methanex Corporation’s position as one of BC’s prominent companies, and its global leadership in methanol production, distribution and marketing. As natural gas is the source for methanol production this trend also benefits the natural gas industry in BC. Ballard Power systems another BC company originally known as the global leader for their work in the development of Polymer Electrolyte Membrane Fuel Cells (PEMFC) for automotive applications switches their focus to the production of DMFC for low power applications. Due to their earlier experience with PEMFC and the similarities between a PEMFC and DMFC, Ballard Power quickly dominates the market and becomes a global leader in DMFC production.

Figure 5-2: Diffusion of Fuel Cell powered Portable Electronics in BC.
Stationary power fuel cells (Solid Oxide Fuel Cells (SOFC) and Molten Carbonate Fuel Cells (MCFC)) although not as in high demand as their portable counterparts also make a reasonable entry into the BC energy system reaching about 5% of market share by 2030. Fuel Cells in automotive applications show the least progress due to the sailing-ship type effect from ICE based automotive technologies which significantly improve their efficiencies and emissions making it harder for fuel cells to compete with it. Furthermore, costs of hydrogen production, delivery and distribution also remain high, adding to the larger cost differential.

However, as fuel cells become more of a household technology and the public become more acquainted with its benefits from the portable and stationary power sectors, it provides automotive fuel cells more time to improve technology costs and to take advantage of the positive public perception of it at a future date.

### 5.3.4 Scenario-B

Scenario-B is characterized with stationary powered fuel cells and natural gas (NG) as the predominant primary energy resource supporting it. The NG resource base, not including coal bed methane, is approximately 115 Tcf (current demand is ~ 1 Tcf/yr). Given that BC is endowed with large resources of NG and that NG is the most appropriate fuel for stationary powered fuel cells, they form a unique techno-economic co-dependency that supports each others’ growth. Two main driving forces that favour the diffusion of stationary power units in BC in this scenario are: (a) supply-side challenges for BC hydro to meet consumer electricity demand past 2014 and (b) rapid improvements in R&D and lowered costs of stationary power fuel cells. Thus natural gas powered generation from stationary fuel cell units help reduce some of the demand for
electricity. Part of the acceleration in the development and commercialization of stationary fuel cells is a result of increased government support for stationary fuel cell development and the noted synergy between NG and fuel cells to help ease the electricity supply shortfall.

The provincial government introduces the policy which gradually phases out the inefficient base-board electric heating and only permits the use of efficient natural gas heating province wide. This further reduces electricity demand and provides further use for the province’s natural gas.

Given their ability to also produce heat from the high-temperature SOFC and MCFC fuel cells, their diffusion rates are fastest in the industrial and commercial sectors that demand both power and heat (co-generation mode). In addition, since these sectors also suffer from the differential electricity rates introduced by BC Hydro to curtail electricity demand from large electricity consumers, industry and commercial organizations install and share the costs of large stationary power units (1-10 MW) for their own power and heating requirements. Fuel cell producers also get into the business of leasing such units to take advantage of this growing market.

Figure 5-3 below shows the rate of diffusion of stationary power units in BC between 2005 and 2030. The 3500 MW installed power represents roughly half of the electricity shortfall of the province for 2030. The remainder is met through a combination of energy conservation programs (i.e. such as smart growth) and the expansion of small hydro as well as the contributions from tidal energy and wind energy.

89 Assuming a 2% growth rate for electricity demand between 2005 and 2030, the required capacity in 2030 would be 18,000 MW compared to the 11,000 MW in 2005 – hence the expected shortfall of 7,000 MW.
A major challenge however, is that the increased use of NG in this scenario significantly increases the carbon footprint of the power generation sector in BC. Through the 2007 BC energy plan, the people of the province demanded zero net green house gas (GHG) emissions for new electricity generating facilities. Unfortunately, while carbon sequestration technology has improved and is commercially viable for coal based power generation in other parts of North America, the costs for sequestering carbon with natural gas is prohibitive throughout this scenario time-frame. Hence the province opts to buy offsets from agencies which invest in energy projects that help reduce or prevent GHG’s from being emitted. Given that these projects meet the condition of additionality, it
ensures that without such investment those emissions would not have been prevented in the first place.

In this scenario even with the additional costs of investing in such offsetting programs it turns out to be more cost-effective (~20/ton CO2 saved) than investment in cleaner renewable energy projects alone to meet the electricity shortfall. Also with more internationally recognized standards for verifying the validity of the investments (i.e. Gold Standard Certification) the public in BC are more accepting of such offsetting programs to achieve net zero GHG emissions from the increased NG consumption.

Given the emphasis on the electricity supply shortfall in the province, much of the government support and incentives were focused on stationary power fuel cells. As such fuel cell applications in portable electronic devices and in transport do not receive much attention, nor is there much improvement in costs for hydrogen production and delivery. In addition given the improvements in battery technologies and the improvements in ICE based automobiles, hydrogen and fuel cells are a weaker option for the portable electronics sectors and transport.

\[90\] It should be noted that the increased efficiencies of the stationary power fuel cell producing electricity and heat, also enables the offsetting of natural gas that would have been used for heating purposes only. This indirectly reduces total demand for purchasing carbon offsets.
5.3.5 Scenario-C

Transport based hydrogen and fuel cell technologies flourish in this scenario. The demonstration of the five Fuel Cell Vehicles (FCV) and nine Fuel Cell Buses (FCB) during the 2010 winter Olympics in Vancouver brings great attention to fuel cell applications in the transport sector and helps greatly improve public perception of fuel cells in transportation. This also helps alleviate fears about the risks associated with hydrogen. The public perception is further supported by the growing interest to reduce vehicle emissions due to concerns for global warming and air pollution related health impacts. Ballard Power systems, the world leader in the development of PEMFC for automobiles, takes advantage of this situation and begins mass production of fuel cells for BC and other similar markets expanding globally.

The dominance of automotive fuel cell technologies in this scenario is somewhat similar to the industry vision of a hydrogen economy in BC, as outlined in the BC Hydrogen and Fuel Cell Strategy (Connor, Britton et al., 2004). While in their scenario they expected a functioning hydrogen economy by 2020, the necessary market, technology and public policy drivers to support such a vision takes somewhat longer than initially expected, as discussed below.

The 2007 BC energy plan mandated zero net GHG emissions from all new electricity generating facilities, which in 2015 is extended to include electricity generation as well as other forms of secondary energy production such as hydrogen, methanol etc. The primary motivation for the extension of the net-zero carbon policy to other secondary energy
carriers was due to the growing acceptance and improvements in the technology and costs of geological sequestering of carbon dioxide globally.

Given the enormous resource base of coal in the province of 23 Billion tons (more than 100 times what is required to meet the province’s energy needs for the next 120 years – BC Ministry of Energy and Mines) and the improved perception of geological sequestering of carbon dioxide, around the year 2020 British Columbians decide to explore coal gasification for hydrogen production and carbon sequestration for moving toward a zero carbon hydrogen based transport system. In addition to the public concern over emissions from the transport sector in populated areas, a powerful driver for the move toward a hydrogen based transport system is the global supply and demand balance of petroleum. As a result of the high price of oil (from dwindling reserves) in excess of $150/bbl in 2015, most competitors of petroleum based technologies appear far more attractive between 2010 and 2020 than they were in the first decade of the 21st century. Furthermore, expectations of a future price on carbon emission, accelerates the development of carbon sequestration and opens the possibility for a carbon neutral coal based hydrogen energy system.

As far as the hydrogen distribution system is concerned, between 2010 and 2020, hydrogen is transported in trucks in the form of compressed hydrogen from the coal gasification plants to the hydrogen re-fuelling stations. However as demand increases, it becomes more cost-effective to develop a hydrogen pipeline infrastructure (Ogden, 1999b) in BC. Given the success with such systems in California and Germany, BC is
able to take advantage of their technology and apply it cost-effectively after 2020 to further develop its hydrogen based transport system.

Given these socio-economic factors discussed above, by 2030 the market share of hydrogen based fuel cell vehicles reach 20% of total vehicle demand as shown in Figure 5-4 below. Based on this trend the projection for 50% market penetration is expected sometime around 2040. This makes the characteristic diffusion time-frame for fuel cell vehicles approximately 30 years. This should be compared with the relatively short diffusion time frame of 12 years for automobiles (replacing horses) in the early 20th century. Since FCVs do not offer the substantial increase in performance that automobiles did compared to horses, even though the re-fuelling infrastructure was very different in both cases compared to its predecessor it can be expected that FCVs would take longer to diffuse. In contrast the assumption here is slightly more optimistic than the diffusion timeframe of 40 years estimated by (Victor, Heller et al., 2003).
Given that oil price, public concerns over emissions and improvements in carbon sequestration and cost of fuel cells for transportation were the main drivers for this scenario, fuel cell applications in portable electronics and stationary power were affected to a far less extent. As such even by 2030 the diffusion of fuel cells in the portable electronics and stationary power sectors is still in its early stages.

5.3.6 Scenario Discussion

The 3 scenarios described above suggested alternative trajectories for the development of hydrogen and fuel cell systems for BC up to 2030. For simplicity each scenario focused primarily on one primary energy source and one end-use application sector. The underlying socio-economic, market and political drivers for each scenario also varied
significantly. As such the uncertainties in each scenario were captured through the variation of the underlying driving forces and the resource and technology dynamics.

The primary driver for scenario-A was the rapid increase in demand for portable power and the inability of battery technology to meet that demand. Given that the world’s largest methanol producer resides in BC and our large natural gas resources, this provides a plausible pathway for the realization of portable power driven hydrogen and fuel cell scenario. In scenario-B the primary driver is the province’s electricity shortfall in 2014. Again given the province’s large natural gas resource and its unique synergy with stationary powered fuel cells it provides for the realization of a stationary power driven fuel cell scenario for BC. Finally in scenario-C the main driver is emissions and air pollution which puts the focus on the transport sector. Here given the enormous coal resources of BC and the improvements in carbon sequestration technology internationally, BC is able to develop a zero-carbon hydrogen based transport system. The presence of local expertise from Ballard Power systems also helps facilitate the development of this scenario.

While a unique set of technology and resource dynamics as well as market and socio-political conditions gave rise to each scenario, it should be noted that various combinations of these driving forces may also give rise to scenarios that have elements of each of the 3 scenarios above. The purpose above was primarily to illustrate how given the uncertainties in the underlying driving forces, how their variation can give rise to entirely different plausible hydrogen and fuel cell futures.
Finally, these scenarios should be compared with the only hydrogen vision presently available for BC, which is outlined in the BC Hydrogen and Fuel Cell Strategy (Connor, Britton et al., 2004). Although this vision places a greater emphasis on automobiles, it also expects stationary fuel cells and portable powered fuel cells to make a significant market penetration (by 2020). They also did not identify the primary energy source/s that would produce the secondary energy carrier (i.e. methanol, hydrogen, etc.) for the different applications; neither did they identify the socio-economic, techno-economic or political forces and their uncertainties that might steer the future in alternative directions. As such, the 3 scenarios described above provide a more comprehensive basis for exploring some of the uncertainties in the socio-technical landscape and regimes that might affect hydrogen futures in BC.

As mentioned in the beginning of this chapter, from section 5.4 onwards we will return to the main manuscript chapters, discuss the relationships amongst them, the main conclusions of this dissertation, the significance of the research within this dissertation, applications of the research and final comments on future research.

### 5.4 Relationship between Manuscripts

As shown in Figure 5-5 below (extracted from Ch1 Figure-4 or Figure 1-4), the preliminary sustainability assessment of the BC Hydrogen Highway conducted in chapter 2, pointed towards the importance of a more comprehensive analysis of sustainability assessment. Upon further investigation into the assessments (sustainability and otherwise)
conducted on energy systems, it became clear the need for a systematic approach to the selection of tools, before actually carrying out the sustainability assessment itself. This led to the development of the framework proposed in chapter 3 (SAF) which suggested an approach to the selection of tools. This placed the emphasis on the importance of designing the sustainability assessment process, before embarking on the assessment. This was referred to as the *sustainability-driven* approach to informing energy and technology policy (see Figure 5-5).

**Figure 5-5: Schematic of the relationship between Manuscripts.**

Chapter 2 also recognized the importance of (a) long time scales involved in energy system transitions, (b) the technology diffusion literature, (c) analyzing past technology predictions, and (d) the co-evolution of technology and society, and recommended that all these factors be considered when planning a path between present and future energy
systems. This provided the motivation to analyze each of these in detail in order to further inform energy and technology policy. This was the topic of chapter 4 and was referred to as the transition-dynamics driven approach to informing energy and technology policy (see Figure 5-5).

Energy systems, in particular hydrogen energy systems and futures, provided the context in which some of the ideas in this dissertation were developed. This provided a common thread binding all manuscripts together. Given that each manuscript will be published in different journals, this commonality is only evident when they are viewed within the context of this dissertation. This common theme provided some substance for the analysis of sustainability and facilitated the thinking about transitions to future energy systems. Finally, chapter 4 also points back at chapters 2 and 3, when suggesting that FCVs may actually need to demonstrate their sustainability benefits in order to increase their competitive advantage over their competitors.

One of the levels of the multi-level-perspective (MLP) model discussed in chapter 4 is the socio-technical niche (ST-niche), defined as a protected space where new technologies may be experimented with. While the Hydrogen Highway project was not discussed within chapter 4 itself it is an example of a real-life ST-niche. As discussed in chapter 2, the Hydrogen Highway project has been described by its developers as a large-scale demonstration and deployment program intended to accelerate the commercialization of hydrogen and fuel cell technologies across a number of locations/nodes in the province of BC. Few if any of the technologies that will be
demonstrated at the 2010 Olympics are likely to be commercially viable by 2010, even within any market niches\textsuperscript{91}. However, they may be sustained by subsidies and strategic investments throughout the project lifetime. As such according to the differentiation of niches into technological and market niches (Geels, Frank W., 2005), the Hydrogen Highway project may be described as existing within a ST-niche. While the term \textit{Hydrogen Highway} itself has been described as a metaphor for the transition to a future hydrogen economy (National Research Council Canada, 2004) the ultimate evolution, co-evolution and transition of the niche technologies (within the Hydrogen Highway project) into a future energy system may not be regarded as an autonomous process. How such a process might occur will be discussed in more detail with the main conclusions (section 5.5).

Another theme that tied the different manuscripts was that of integration. At this level, chapter 2 was about how to integrate the quantitative and qualitative information and chapter 3 was about a systematic approach to integrate tools developed across a variety of different disciplines and practices. The general message is that no one tool on its own emerges as being powerful enough and widely applicable to be suitable for sustainability assessments, and therefore the integration of tools is a necessary component of sustainability assessments. Section 5.5 below describes further what the main tool types

\textsuperscript{91} The notion of a niche may be differentiated into technological niche and market niche (Geels 2005). Although a niche technology could be operating in either of these niches, in the case of the former it may be sustained by subsidies and strategic investments while in the latter it may be sustained by regular markets (although small) on their own or in combination with subsidies and strategic investments. Also in the former, design rules and users are often not properly defined or articulated and thus are more unstable than the latter.
are, how they may be integrated and how the different assessment processes may be coordinated.

Integration was also a central concept in chapter 4 as it attempted to integrate the insights from a variety of different literatures (collectively referred to as TTDM), in order to offer a new way of thinking about transitions. Integration of these literatures were necessary as they are often treated separately, although they each contribute significantly toward the common understanding of technological change and transitions. The significance of the integration among this literature is discussed in more detail in section 5.6.

At a conceptual level it is also worth noting the concept of 'levels' that emerged in chapter 3 in the context of the 'framework level' and the 'analytical level'. In chapter 4 the notion of levels was manifest in the multi-level-perspective (MLP). Each of these levels was fundamental to the discussions in their respective chapters.

These other inter-connections that exist between the different manuscripts are shown by the 3 smaller arrows that connect the 3 chapters to each other in Figure 5-5, apart from the 2 main arrows that point from chapter 2 to chapters 3 and 4.
5.5 Main Conclusions

Complex decisions need to be made with regards to the sustainability and possible transition to an energy future more desirable than today’s energy systems. To this end, two main approaches may be pursued when informing energy and technology policies for future energy system changes: the sustainability driven approach and the transition-dynamics driven approach.

1) SUSTAINABILITY-DRIVEN APPROACH: The Sustainability Assessment of energy futures

I. The assessment of sustainability was only a minor component in the literature on hydrogen energy futures and systems. This is also found to be true for the field of energy studies in general.

- Hydrogen and Fuel Cell energy systems
  a. Hydrogen energy is not a renewable source of energy. Given the variety of fuel production pathways (fuel chains - many of which are fossil based) the sustainability of hydrogen futures cannot be presumed in advance. An explicit assessment is necessary in the interest of a likely desirability of a sustainable energy future.
  b. While hydrogen energy conversion devices such as fuel cells may be considered as low emission devices, given the fuel cells’ greater efficiencies, and their relatively high energy and material requirements, the production of fuel cells must also be
taken into account as part of a comprehensive sustainability assessment.

II. Sustainability Assessment may be regarded as the next generation of assessments (Rotmans, J., 2004b). Sustainability assessment requires not only the assimilation of knowledge across multiple expert domains but also the application and integration of a variety of assessment tools across a variety of disciplines and cross-disciplines.

• Given the demands of the process, it would call for a team of experts with complementing expertise, perhaps co-ordinated by a lead sustainability assessment practitioner (L-SAP) (or through a collective process). The most important tasks of such an L-SAP would be in overlooking the entire process, being aware of the needs of the individual experts and engaging in a discussion with experts as well as the public in identifying the sustainability context appropriate for the assessment.

III. The tool selection process is a crucial step in the design of any assessment for sustainability. Given the possible influence of the sustainability assessment tools themselves on the assessment process, a transparent and systematic approach to tool selection is necessary for the design of sustainability assessments. Due the novelty of sustainability assessment itself, such a process has not been developed to date, and most attempts
seem to follow an arbitrary approach to the selection of tools based on convenience, familiarity and availability. The sustainability assessment framework proposed here, provides a transparent and systematic approach to the above problem.

i. The SustainabilityA-Test tool-set may be considered as a one-stop-shop for the tool selection for sustainability assessments.

ii. The universe of assessment tools may be classified into two fundamental levels – framework level and analytical level.

   a. Analytical level tools perform specific functions, are based on specific algorithms and thus provide high analytical precision.

   b. Framework level tools have a greater scope and flexibility, which enable them to compensate to some extent for the weaknesses of the more analytical tools and methods.

iii. The framework level tools facilitate the systematic study and analysis of the problem domain, the result of which will be the identification of the most appropriate tools/expertise for the assessment (as opposed to pre-selecting the tools in advance). Such a process will also inform and guide the public consultation process for refining the objectives and criteria as well as the options to be considered within the assessment.

iv. The inclusion of the framework level tools ‘IA approach’ (integrated assessment approach) and the ‘MCA process’ (multi-criteria assessment process), is introduced as a minimum condition for
designing sustainability assessment processes. The IA approach may be described as “a process that integrates knowledge from across different disciplines and stakeholders in order to understand complex issues and offer integrated insights to decision makers” (Rotmans, J, 1998; Rotmans, J & Dowlatabadi, 1998), while the MCA stages which are common to all Multi-criteria assessments (stages 1-3) are collectively referred to here as the MCA process. These together capture the core or most common aspects of sustainability.

vi. Most of the conceptual challenges of sustainability assessment (i.e. issues of scale, complexity, incommensurability, equity, problem framing, uncertainty, knowledge gaps etc.) need to be dealt with at the framework level as they are fairly broad in scope and beyond the scope of most analytical tools.

2) TRANSITION-DYNAMICS DRIVEN APPROACH: The consideration of past technological transitions, technology diffusion and results from modelling technical change

I. The literature on hydrogen energy futures had only limited discussions of past energy system transitions and dynamics, and often consisted of simple comparisons and extensions of technology diffusion and transition processes when making technology comparisons or policy recommendations for future transitions. Such analyses and
recommendations simply ignore the complexity of socio-technical systems and their transition-dynamics.

- The heterogeneity on the demand side (i.e. different fuel cells in different application domains) is particularly important as they give rise to different barriers for technology diffusion. In general, the explicit consideration of both supply and demand sides is important when informing policy on the suitability of a future hydrogen economy.

II. The TTDM literature revealed a number of valuable insights for energy system transitions. They range from, insights about the complexities in the early phase of the diffusion process - such as the ability for existing and novel technologies to co-exist in a hybrid form (technology symbiosis); the possibility of a rebuttal from the existing technology regime (sailing-ship effect); the typically long times scales of diffusion for large infrastructures (50-100 years) – due to the existing technological co-dependencies as well as the complex web of interactions with the economies, societies and cultural practices in which they are embedded; the observation of a saturating technological cluster at present – implying a window of opportunity for a possible technological transition; the importance of early investment across a diverse set of technologies to hedge against future uncertainty; the failures of predictive forecasts and policies based on them – suggesting the need for a scenarios based analysis; the suggestion of a
variety of different contexts for future transitions - depending on the degree of co-ordination of regime actors and resources available to the regime; to the theoretical construct of the multi-level perspective – which emphasizes the need to consider the 3 levels of niches, regimes and landscapes of socio-technical systems.

III. While the above insights are indeed valuable and improve our understanding of the dynamics of technological transitions, they are not intended to provide any guidance with regards to the direction of a possible future transition. With the exception of the technological transitions literature, the literature on systems of technologies and infrastructures and the technology modelling literatures largely operate at the level of technologies and their various combinations. However, the future energy system is not just about a collection of technologies but exists within a socio-technical system. Thus the transition is made not to a set of technologies but to a socio-technical system. Since the TTDM literature is not intended to provide guidance for future transitions, we may need to turn elsewhere for that purpose.

i. This leads us to an alternative way of thinking about socio-technical change and transitions, which is not in terms of the currency of technologies, but in terms of a desired future and its more broad ranging characteristics. If such a choice or vision emerges through a collective social-learning process then perhaps this can gradually influence the values, beliefs and cultural aspects of the ST-landscape; which in turn could affect the operation of the various institutions that govern the rules of the ST-regime.
This would then further enable the niche technologies to co-evolve and develop inter-dependencies with other compatible technologies and systems, thus initiating a possible socio-technical transition compatible with the broader desired future.

ii. The above suggests a top-down approach to socio-technical transitions, compared to the traditional niche-to-regime bottom up approach.

Both the sustainability-driven and transition dynamics-driven approaches are equally important for informing energy and technology policy regarding transitions to future energy systems. They should be viewed as being complementary to each other. While, the sustainability-driven approach allows us to assess and compare the sustainability of future technologies and systems, the transition dynamics-driven approach informs us about the dynamics of the transition process and also urges us to think about the transition in terms of a desired future and its characteristics (i.e. sustainability characteristics). Together the two approaches better inform us on how we might think about choosing and making transitions toward a desired future.

5.6 Significance of this Research to the field of Study

The preliminary sustainability assessment of the BC Hydrogen Highway in chapter 2 is to my knowledge one of the first attempts to characterize and assess the sustainability of any real hydrogen energy system (or hydrogen futures). Although there are no large scale hydrogen energy systems worldwide, there are a number of small-scale hydrogen energy systems in Europe, United States and in Canada. Therefore, it is hoped that this work
would set precedence to the sustainability assessment of both current and future hydrogen energy systems.

It was also argued (chapter 3) that the few attempts in the literature to conduct a sustainability assessment seemed to have a rather arbitrary approach to the selection of the sustainability assessment tools. The arbitrariness may be attributed to practitioner biases such as convenience, familiarity and availability of particular tools. Given that the selection of tools itself can affect the results of the sustainability assessment, a framework was developed and proposed (the Sustainability Assessment Framework - SAF) in order to provide a more systematic approach to tool selection and to aid in the design of sustainability assessments. While the process characterized by arbitrary tool selection may be referred to as a first-order sustainability assessment (FOSA) (Roberts & Robinson, 2007), the systematic approach offered by the SAF may be called a second-order sustainability assessment (SOSA).

It should be pointed out that the framework for tool selection was built upon a significant body of literature that has emerged from the European Commission on Sustainability Assessment tools – namely the SustainabilityA-Test project. While the SustainabilityA-Test provides an excellent resource for the practitioner of sustainability, providing guidance on how to select among these tools was not within its scope. Therefore, the Sustainability Assessment Framework proposed here for the tool selection and design of the sustainability assessment, further enhances the utility of the European Commission’s SustainabilityA-Test project.
Another major contribution of this research was in the area of socio-technological change and transitions. While a number of different empirical and theoretical literatures exist that focus on various aspects of technical change, there appeared to be little cross-talk or interaction between them\textsuperscript{92}. Furthermore, given their somewhat different areas of focus, the language used and developed within each of these literatures also evolved accordingly. This perhaps inadvertently created barriers between them and may have made it difficult for their unified and integrated treatment. Given the importance of the results that emerge from each of these literatures for the discussion of technical change of energy systems, a serious effort was made to unify and integrate the results from these related but somewhat disparate literatures.

This was attempted in the following manner. First, hydrogen and fuel cell futures were used as the common theme throughout the discussion which helped in bringing together the TTDM literature. Second, the multi-level-perspective from the technological transitions literature also served as a conceptual and linguistic aid in binding the discussion on future energy systems. In so doing, the goal was to attempt to harness the collective insights and offer an alternative way of thinking about energy system transitions and more appropriately about socio-technical transitions, that may not have emerged if the literatures were treated in isolation.

The new insights that emerged from the combined application of the results from the TTDM literature may be compared to the idea of new combinations and functionalities

\textsuperscript{92} These are the literatures on technology diffusion, technological transitions and the modelling of technological change, collectively referred to as TTDM within this dissertation.
that emerge from the interaction and co-evolution of technologies. In this case the new combinations are between the different literatures and the new functionalities may be seen as the integrated insights that emerge about energy system transitions.

At an even higher level of aggregation (across all manuscripts), the research within this dissertation may be seen as existing at the confluence of 3 even larger areas of study (discussed in the introductory chapter). As shown in Figure 5-6 below, they are the literatures on Hydrogen Futures (and hydrogen systems), Sustainability Assessment and Technological Change. While customarily sustainability assessment and technological change literatures rarely overlap, since the sustainability of a future energy system would likely be a characteristic of a desirable future, the assessment of sustainability as well as the transition to such a future end-state would be a necessary exercise. To this end the sustainability-driven approach as well as the transition-dynamics driven approach facilitates the convergence of these largely separate fields of study.
If one chooses to focusing on the hydrogen futures literature (or energy futures), this research emphasizes the inclusion of sustainability assessment as well as explicit consideration of the technological change literature, when discussing transitions to future hydrogen based economies. Such considerations will no doubt add more texture and context to explorations of hydrogen futures.

5.7 Potential Applications of Research Findings

While the motivation to the sustainability assessment framework (SAF) came from the energy sector, it was developed so as to be generally applicable to any sustainability assessment process. For instance, the SustainabilityA-Test tool-set, which may be used with the SAF, contains over 50 different assessment tools and methods. These are not just
assessment tools used for energy sector applications, but tools and methods that may also be used for the assessment of sustainability within other problem domains. As a result although the SAF was applied (partially) in chapter 3 to light duty vehicles within the transportation sector, given the framework’s generalizability, it may be applied to other transport applications as well as to applications within any other sector.

Given the present arbitrariness and one-size-fits all approach to tool selection and sustainability assessment, the application of the SAF (to conduct a second-order sustainability assessment) will make the sustainability assessment process more systematic, transparent and defensible. Based on their findings from analyzing global environmental assessments (Mitchell, Clark et al., 2006a) suggest that the assessments are likely to be more influential to political and economic decision makers “if the process is perceived not only as scientifically credible but also as salient to policy concerns and as generated through legitimate means”. These enhancements offered here to the design of sustainability assessment should help sustainability assessments to become more salient, credible and legitimate.

Another research finding was that the sustainability assessment process is a non-trivial exercise. Therefore any attempts to cut-corners and simplify it may hinder the progress toward developing the science of sustainability. Given the enormity of the task and the relative infancy of present day sustainability assessments, it was pointed out that there is a need for a new breed of practitioners for this new generation of assessments. Thus the above finding would seem to suggest that more emphasis be given to training and
building capacity for the next generation of sustainability practitioners, in order to further develop and sustain the practice of sustainability assessments.

It is expected that in the future the hydrogen futures literature will place greater emphasis on a more explicit discussion and analysis of sustainability as well as consideration for the various insights about the dynamics of technological transitions that emerged from the TTDM literature. It is hoped that the application of these considerations will result in more meaningful comparisons between different technologies as well as their diffusion and transition dynamics.

Furthermore, it is recommended that the guidance for a transition towards a future energy system emerge from the discussion occurring at the level of a desirable future rather than from a discussion at the level of technologies. Even the former will not guarantee a transition in the desirable direction given that transitions are essentially a result of a mixture of intended and unintended outcomes of historical processes (Berkhout, Frans, Smith et al., 2004). While this may be the best-case scenario, thinking about transitions in terms of a desirable future is likely to increase our chances of guiding a transition than by relying on predicting the future or by making choices at the level of technologies.

In the introductory chapter it was noted that a group of leading international natural scientists, social scientists and policy analysts had proposed eight core questions to guide the research needs of Sustainability Science (Kates, Clark et al., 2001; Swart, Raskin et al., 2004). To a large degree this dissertation derived its motivation from this

93 Seven of these were proposed by Kates et al., 2001 and the 8th by Swart et al., 2004.
emerging paradigm. It is hoped that the applications of the ideas and recommendations that emerged from the research within this dissertation such as, the importance of systematically selecting and then integrating sustainability assessment tools, the importance of integrating the insights from the TTDM literature as well as that of guiding transitions based on an articulation of desirable futures rather than technologies, go some way in making a contribution toward the field of sustainability science.

5.8 Comments on Future Research

Sustainability and the Hydrogen Highway: The tool selection and design of the sustainability Assessment conducted on the BC Hydrogen Highway (Roberts & Robinson, 2007) in chapter 2 was not based on a systematic approach (this was a first-order sustainability assessment - FOSA), as argued for in chapter 3 (second-order sustainability assessment - SOSA). This suggests a SOSA of the BC Hydrogen Highway should be undertaken. While part of the motivation for chapter 3 came from chapter 2, in return, the Sustainability Assessment Framework (SAF) for the tool selection and design (chapter 3) may be applied back to designing the sustainability assessment for the BC Hydrogen Highway – however, this should be done through a properly designed stakeholder and public engagement process. Also, data collection for chapter 2 was done over a year ago, so by now it is likely that more data would be available for the assessment. If the data is quite different than that used in chapter 2 (Roberts & Robinson, 2007), then it may be important to note that the outputs of the two assessments (pre-SAF and post-SAF) may be quite different.
Furthermore, as argued earlier in this chapter, the Hydrogen Highway project did not attempt to map out the inherent uncertainties involved in making a transition to a hydrogen energy future in BC. The uncertainty in possible hydrogen futures are in turn driven by the inherent uncertainties in a variety of underlying socio-economic, political and techno-economic forces within the socio-technical landscape and regimes. While 3 coherent hydrogen energy scenarios were outlined above (section 5.3) they were largely qualitative with some attempt at quantification. As such, it presents an opportunity to quantify some of the outcomes based on the underlying assumptions in each of the scenarios.

**Sustainable Transport Systems:** Given the examples of transport systems referenced within the main manuscripts and the discussion on sustainability assessment in chapters 2 and 3, it seemed appropriate to also explore the concept of sustainable transportation within this dissertation (section 5.2). As discussed, the sustainability of a given transport systems is strongly linked to land-use planning and community development. A number of different policy alternatives were identified as well as a list of metrics that may be used in monitoring progress toward sustainable transportation. A future task may be to test the applicability of these metrics in monitoring the sustainability of a real-life transport system and to further develop it so that it is more comprehensive and widely applicable to most transport systems worldwide.

**Co-ordination of Sustainability Assessments:** In chapter 3 most of the effort was on the development of the SAF. In the application section a preliminary second-order-
sustainability assessment (SOSA) was conducted on the problem domain of light-duty vehicles. A more complete application however should be conducted through a participatory public/stakeholder process. Based on the resulting recommendations for analytical level tools the actual sub-assessments would then be carried out, while being cognizant of the implications of the various conceptual challenges of sustainability assessment - as there are no widely accepted and applicable methods presently to resolve these challenges, research on such methods would also be a useful contribution. Each of the sub-assessments requires special expertise, has different data needs and thus requires special attention. The next step of that research would be to conduct a comprehensive sustainability assessment that integrates the results of the separate ancillary assessments.

For this phase it is important to recognize (a) that many of the ancillary assessments may be conducted in tandem (with the exception of those that may be completely nested with each other or connected sequentially) to save time, and that (b) there is good communication between the various groups in order to understand each others’ data requirements and that the integration is conducted in a consistent and transparent manner. Such a process may be co-ordinated by a lead sustainability assessment practitioner (L-SAP) who oversees the entire process of integration or it may be done through a collective effort. The key however, is integration - and its success is likely to depend on effective communication, transparency and consistency.

**Sustainability Heuristics:** The next step of actually conducting the comprehensive sustainability assessment would need significant time and resources. While these are often limited, given the complexity of the sustainability assessment process, any attempts
to simplify it without consideration of the impacts of the omission could potentially jeopardize its intrinsic value. Therefore, in the interest of improving the practice of sustainability assessment (and sustainability science in general), first experience needs to be built in carrying out these somewhat complex and comprehensive sustainability assessments in different problem domains. Then it may be possible to simplify the process into sustainability heuristics, within a given problem domain. Such sustainability heuristics would be a valuable contribution to sustainability science. However, it may only come after sufficient understanding and experience has been gained from conducting comprehensive sustainability assessments within different problem domains.

**Typology for Sustainability Assessments:** In the interest of developing sustainability assessments, it may be necessary to classify the different assessments based on their level of rigour. In chapter 2 the idea of a *first-order-sustainability assessment* (FOSA) was introduced (Roberts & Robinson, 2007). This refers to a ‘sustainability’ assessment in which no explicit thought or effort is given to the tool selection process, thus the tool selection and design of the assessment is not a result of systematic process. Chapter 3 introduced a framework where this process is more systematic and transparent and so the tools used for the assessment are not chosen arbitrarily but emerge from a systematic analysis of the problem, the result of which is the identification of the most appropriate tools and expertise for the assessment. This is referred to as a *second-order-sustainability assessment* (SOSA). Perhaps the next level in which the entire assessment is carried out may be more suitably referred to as a comprehensive sustainability assessment (CoSA). While this may be one approach to classify sustainability assessments based on their level
of rigour, other approaches may exist that may be more appropriate. The point made here however, is that the development of such a typology may enhance the overall quality of sustainability assessments, as they get classified into the different categories/levels.

**Socio-Technical Change:** The conclusions drawn in chapter 4 about guiding socio-technical change emerged from the integrated insights from the three main literature areas explored (socio-technical transitions, diffusion of systems of technologies and infrastructures and on the modelling of technical change). While institutions and governance structures were implicit in the discussions about the multi-level perspective, given the growing literature on the role of institutions and governance in affecting social change, a more explicit treatment of this literature in combination with the above literatures would be warranted and possibly lead to further insights which would enhance our understanding about guiding socio-technical change.

**Modeling Choice:** A major conclusion of this research as identified in section 5.5 is the suggestion that an alternative way to think about transitions may be in terms of the choice about a desired future and its broader characteristics. It was also pointed out in chapter 4 that the concept of choice is more complex than is often represented in conventional scientific discourse and policy circles. Perhaps the inspiration from the MLP, may lead us to conceive of the concept of choice also as being operational at different conceptual levels. Thus it may be useful to model the concept of choice at the different levels at which it may exist and explore their implications for the policy process.  

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94 Some economists have attempted to model consumer choice through discrete and continuous choice models. However, the choices that are modeled in this way are those made at the technology level only.
In closing, a word needs to be said about choices, decision-making and futures policy - after all an important goal of this dissertation was to better inform policy. Past energy and technology forecasts as well as present energy modelling and energy policy seem to beg the question of technology choice. As mentioned earlier, given that technologies are but one dimension of the larger socio-technical system, choosing technologies for our future may be like trying to get the ‘tail to wag the dog’. It may be reasonable to conjecture that at the most basic level, in terms of energy, what the public may really care about is energy services which are affordable and high quality energy carriers (Nakicenovic, Nebojsa, Grübler et al., 1998), and in terms of a future, qualities such as a clean environment and peace where people may live and work freely. While few among the public would insist that in the future their automobile should be powered by an internal combustion engine running on gasoline or diesel, certain institutions both private and public may have an interest in maintaining the status-quo.

If the future is to some extent determined by institutions and if the institutions do not represent the desires and wishes of the public, then this points to a systemic problem in the decision-making process. In order to bridge this gap and to allow the flow of information from the public to the decision makers, more active methods (other than casting votes at an election) such as participatory methods may be necessary (Robinson, J.B., 2003; Swart, Raskin et al., 2004; Tansey, Carmichael et al., 2002). Such methods attempt to incorporate the values and preferences of the public in articulating desired
futures. Viewed from this level of desired futures, energy and technology policy itself becomes part of a larger policy framework - that of *futures policy*.

To put it another way, if economic policy or environmental policy or energy and technology policy etc., all operate independently of each other, without being guided by a coherent policy framework (informed by common characteristics of desired futures), then the result may be a set of inconsistent policy decisions; and since the public is affected by all these different policy decisions simultaneously, the future trajectory or the montage of the future world we may be painting, may be best characterized as *stumbling along*. 
5.9 References


Appendices

Appendix-A: GHGenius 3.3

Scope: GHGenius focuses on the life cycle assessment the different fuels for transportation, both at present and in the future. Since transportation fuel pathways require energy and material inputs from across the economy it consists of emission results for other energy systems beyond transportation fuels. The model can predict emissions for past, present and future years through to 2050 using historical data or using correlations for changes in energy and process parameters over time that can be stored in the model. GHGenius can model regions within Canada (east, central or west) and some provinces for many of the processes. It can also model USA and Mexico (whole country).

The model includes all steps in the life cycle from raw material acquisition to end-use. The fuel-cycle segments considered in the model are given below.

- Feedstock Production and Recovery
- Fertilizer Manufacture
- Land use changes and cultivation associated with biomass derived fuels
- Leaks and flaring of greenhouse gases associated with production of oil and gas
- Feedstock Transport
- Fuel Production (as in production from raw materials)
- Emissions displaced by co-products of alternative fuels
- Fuel Storage and Distribution at all Stages
- Fuel Dispensing at the Retail Level
- Vehicle Operation
- Carbon in Fuel from Air
- Vehicle assembly and transport
- Materials used in the vehicles

For light-duty vehicles (LDVs) the model can analyze emissions from conventional and alternative fuelled internal combustion engines vehicles, battery powered electric vehicles and light duty fuel cell vehicles. For heavy-duty vehicles (HDV), both internal
combustion engines and fuel cell powered class 8 heavy-duty trucks, urban buses, or a combination of buses and trucks can be modelled. There are currently more than 140 vehicle and fuel combinations possible with the model. In addition, GHGenius also models the emissions associated with the electric power generation.

**Model Data:** Data used within the model for Canada are obtained from Statistics Canada, Natural Resources Canada, Environment Canada and the National Energy Board. These sources provide information on the production of power, crude oil, refined petroleum products, natural gas and coal production. Industry associations such as the Canadian Association of Petroleum Producers (CAPP) and the Canadian Gas Association (CGA) have also been used as sources of data. While GHGenius contains the data for all of the processes included in the model, the user can readily make changes to many of the steps in the lifecycle (through an input sheet), in order to customize the LCA to their particular needs. The user can also make changes in many of the specific steps in the life cycle to develop a better understanding of the sensitivity of the processes to these changes.

**Impact Assessment:** The model is capable of estimating life cycle emissions for three impact categories – primary greenhouse gases, criteria pollutants from combustion sources and energy used.

The Greenhouse Gases within the model are Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O), Chlorofluorocarbons (CFC-12), Hydrofluorocarbons (HFC-134a). GHG emissions are also calculated for the carbon dioxide equivalent emission. The user can choose to use the Intergovernmental Panel on Climate Change (IPCC) 100 year global warming potentials (GWP) or other values based on user preference. For greenhouse gases GHGenius can assess the cost effectiveness of various strategies using the results from the lifecycle assessment and the fuel and vehicle costs that are input by the users.

Other Air Contaminants modeled are Carbon monoxide (CO), Nitrogen oxides (NOx), Non-methane organic compounds (NMOCs), Sulphur dioxide (SO2) and Total Particulate Matter. The non-methane organic gases are also weighted according to their ozone forming potentials.
Total Energy used consists of:

- Total and fossil energy used per unit of energy produced for each stage of the fuel production steps,
- Total energy used per kilometer driven for the fuel used in light duty internal combustion engines, light duty fuel cell vehicles, heavy duty internal combustion engines, and heavy duty fuel cell vehicles,
- Fossil energy used per kilometer driven for the fuel used in light duty internal combustion engines, light duty fuel cell vehicles, heavy duty internal combustion engines, and heavy duty fuel cell vehicles
- The proportions of types of energy used for each stage of the fuel production cycle.

Model Outputs:

- CO2-equivalent emissions (in g/km) by stage of fuel-cycle and for vehicle manufacture, for the feedstock/fuel/vehicle combinations identified above,
- Summary of % change in lifecycle g/km emissions from alternative-fuel vehicles, relative to conventional gasoline LDVs or diesel HDVs,
- Emissions (in g/km) by individual pollutant for each stage of the fuel-cycle for each feedstock/fuel,
- Emissions from EVs by region,
- CO2-equivalent emissions (in g/GJ) for each stage of the upstream fuel-cycle for each feedstock/fuel,
- Emissions (in g/GJ) by individual pollutant for each stage of the upstream fuel-cycle for each feedstock/fuel,
- Emissions from electricity use: CO2-equivalent emissions (in g/kWh delivered) for different sources of electricity generation,
- Emissions from use of heating fuels: CO2-equivalent emissions (in g/GJ-heat delivered) for natural gas, LPG, electricity, bio-diesel and fuel oil;
- The cost effectiveness of GHGs reduced for each of the vehicle/fuel combinations in the model.

Source for Appendix A: ((S&T)2 Consultants Inc., 2006)
## Appendix-B: Major hydrogen and fuel cell events (1766-2000)

<table>
<thead>
<tr>
<th>YEAR</th>
<th>EVENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1766</td>
<td>Discovery of Hydrogen by Henry Cavendish</td>
</tr>
<tr>
<td>1783</td>
<td>1st Hydrogen Balloon flight by Jacques Alexander Cesar Charles</td>
</tr>
<tr>
<td>1794</td>
<td>1st Hydrogen Generator built</td>
</tr>
<tr>
<td>1800</td>
<td>Electrolysis discovered by English Scientists William Nicholson &amp; Sir Anthony Carlisle</td>
</tr>
<tr>
<td>1839</td>
<td>Discovery of the Fuel Cell effect by Christian Friedrich Schoenbein</td>
</tr>
<tr>
<td>1845</td>
<td>Invention of the &quot;gas battery&quot; (later known as the Fuel Cell) by William Grove</td>
</tr>
<tr>
<td>1874</td>
<td>Jules Verne's &quot;Mysterious Island&quot; and its prediction of a hydrogen future</td>
</tr>
<tr>
<td>1920s and 1930's</td>
<td>Interest in Hydrogen as a fuel in Germany, England and Canada</td>
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<tr>
<td>1920s and 1930's</td>
<td>Development of hydrogen Dirigibles</td>
</tr>
<tr>
<td>1920</td>
<td>First Electrolyser shipped by Canada's Electrolyser Corporation</td>
</tr>
<tr>
<td>1930's and 1940's</td>
<td>Rudolfo Erren's (German engineer) trucks, buses, submarines and ICEs running on H2</td>
</tr>
<tr>
<td>1937</td>
<td>Hindenburg Accident</td>
</tr>
<tr>
<td>1950's</td>
<td>Francis T. Bacon developed the 1st practical Hydrogen-Air Fuel Cell</td>
</tr>
<tr>
<td>1960's</td>
<td>NASA uses Fuel Cell's in Space Program</td>
</tr>
<tr>
<td>1970</td>
<td>The term &quot;Hydrogen Economy&quot; was coined at GM by John Bockris</td>
</tr>
<tr>
<td>1973</td>
<td>Interest in Fuel Cell development sparked by OPEC oil embargo</td>
</tr>
<tr>
<td>1974</td>
<td>1st major International Hydrogen Conference (THEME)</td>
</tr>
<tr>
<td>1974</td>
<td>Creation of the IAHE (International Association of Hydrogen Energy)</td>
</tr>
<tr>
<td>1988</td>
<td>Soviet Union’s Tupolev TU-154 commercial jets converted to run partially on liq.H2</td>
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<tr>
<td>1988</td>
<td>William Conrad - 1st person to fly an airplane running exclusively on LH2</td>
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<tr>
<td>1988</td>
<td>German trials of FC (Siemens) powered submarine</td>
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<tr>
<td>1989</td>
<td>Creation of NHA (National Hydrogen Association)</td>
</tr>
<tr>
<td>1989</td>
<td>Creation of ISO committee for Technical Standards of Hydrogen Energy</td>
</tr>
<tr>
<td>1990</td>
<td>World’s 1st Solar powered hydrogen production plant in Southern Germany</td>
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<tr>
<td>1993</td>
<td>World’s 1st PEMFC Bus built by Ballard Power Systems in Vancouver</td>
</tr>
<tr>
<td>1993</td>
<td>Japan Launched its WE-NET (World Energy Network) project</td>
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<tr>
<td>1993</td>
<td>Daimler-Benz and Ballard Power co-operate to build FC’s for cars and buses</td>
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<tr>
<td>1997</td>
<td>Addison Bain (NASA) proves that Hydrogen was not the cause of Hindenburg Accident</td>
</tr>
<tr>
<td>1997</td>
<td>Daimler-Benz and Ballard Power announced $300 million spending on fuel cell R&amp;D</td>
</tr>
<tr>
<td>1999</td>
<td>Royal Dutch/Shell set up a Hydrogen Division</td>
</tr>
<tr>
<td>1999</td>
<td>Europe’s 1st Hydrogen gas stations were opened in Hamburg and Munich</td>
</tr>
<tr>
<td>1999</td>
<td>Iceland Announced plan for worlds 1st Hydrogen Economy</td>
</tr>
<tr>
<td>2000</td>
<td>World’s 1st production ready Automotive Fuel Cell (Ballard Power, Detroit Auto-Show)</td>
</tr>
</tbody>
</table>
Appendix-C: Hydrogen Production Processes

Steam Methane Reforming (SMR): Reforming of Methane in Steam (700-1000 C, 3-25 bar) in the presence of a catalyst is commonly known as Steam Methane reforming. The SMR process is endothermic and therefore requires an external source of heat to sustain the reaction at the elevated temperatures. Almost all of the hydrogen produced today (~43 metric tones/yr) is from SMR (75%) then petroleum (23%) and only a small fraction from electrolysis (~4%). In terms of uses: oil refining - 43%, ammonia production - 36%, methanol production - 10%. The relatively low price of methane and the efficiency improvements of the reformers make SMR the dominant hydrogen production method.

Gasification: Gasification can be used to extract hydrogen from coal, biomass or other agricultural bi-products and wastes. In this process the feedstocks are gasified at a high temperature (> 700 Celsius) to produce a synthetic-gas (syngas), which is further processed and purified to produce hydrogen at the required purity. This is particularly attractive in areas where coal is abundant. Given that the gasification of these feedstocks produces high amounts of greenhouse gases and other pollutants, it is important to consider upstream emissions during the hydrogen production process.

Partial Oxidation (POX): Partial Oxidation is a process that can be used to extract hydrogen not only from natural gas but also from other hydrocarbons such as gasoline, diesel, methanol, ethanol etc. In this process the hydrocarbons are oxidized to produce carbon monoxide (CO) and hydrogen (H₂). POX has the advantage of being an exothermic reaction and therefore provides its own heat. POX is not used as widely as SMR or gasification due to its lower efficiencies and higher capital costs.

Auto-Thermal Reforming (ATR): ATR is a combination of POX and SMR. The term reflects the heat exchange between the exothermic POX reaction and the endothermic SMR process. In the ATR process the hydrocarbons react in a mixture of steam and oxygen in a thermal reactor in the presence of a catalyst.
**Electrolysis:** Electrolysis of water (Hydrolysis) is simply the splitting of water ($H_2O$) into its constituents of hydrogen ($H_2$) and oxygen ($O_2$) using electricity. Less than 5% of the hydrogen produced worldwide is produced from Electrolysis. The 2 main types of electrolyzers in use today are Alkaline Electrolyzers (Norsk Hydro) and Polymer Electrolyte Membrane Electrolyzers. Alkaline Electrolysers are better suited for grid connected large scale electrolysis while PEM systems are better for units connected to renewable electricity where the output varies greatly. The efficiency of electrolyzers is typically in the 80% range (based on the hydrogen’s Higher Heating Value (HHV)).

**Biological Hydrogen Production:** Hydrogen production from algae, bacteria and other organic materials has been carried out in various research laboratories (e.g. UC Berkley). However, presently the efficiencies are quite low (~ 10%) and the costs uncertain.
Appendix-D: Hydrogen Storage Technologies

Compressed Hydrogen (CH2): This is the simplest of all storage technologies as it only needs a compressor and pressure vessel. The main problem with CH2 is the low storage density, which is a function of storage pressure. Higher storage pressures result in higher capital and operational costs. However, for small amounts of hydrogen stored over short time frames CH2 is cost effective. Typical storage pressures available today are 10000 psi (750 bar). CH2 is generally limited to < 1300 kg due to costs of pressure vessels (Amos, 1998). For greater amounts LH2 or underground storage is more cost effective.

Liquid Hydrogen (LH2): Between -259 and -252 deg C, hydrogen is a liquid. Liquefying hydrogen drastically increases its storage density but the low boiling point it takes almost a third of the energy contained in hydrogen (per unit of energy stored) to liquefy it, making it energetically inefficient. In addition, the cost of the cryogenic equipment and the non-zero boil-off rates can further reduce its energy efficiency. However, for transporting small amounts of Hydrogen in tankers over long distances can be cost-effective as shown by an NREL study (Amos, 1998). In addition, for storage over long periods and for large quantities, LH2 was also shown to be more cost effective than CH2, because the cost of pressure vessels increases faster than liquefaction costs. Also, the boil off rate is inversely proportional to the size of the cryogenic storage vessel. In terms of maintenance cost LH2 has the highest cost compared to any other storage technique. If low cost electricity is available this can reduce the overall costs considerably.

Metal Hydride (Me-H): Metal Hydrides store hydrogen by chemically bonding the hydrogen to the metal. Me-H’s can adsorb the hydrogen at or below atmospheric pressure and release it at higher pressures when heated. Hydrides have a high volumetric storage density but very low gravimetric storage densities. Hydrides typically only store between 2-6% by weight (Amos, 1998; Ogden, 1999b). This makes Me-H a poor choice for hydrogen storage in automobiles but for stationary storage where size (volume) is of more importance than weight Me-H has the advantage. Me-H can be cost-competitive
with CH2 for small quantities of hydrogen and especially attractive when hydrogen is produced at low pressures but when high pressure hydrogen is required. For large quantities of gas Me-H is not a suitable option due high capital costs. When a source of waste heat is easily available this can be used to reduce the energy costs for releasing the hydrogen from the Me-H. In terms of maintenance costs Me-H has the lowest costs.

**Glass Microspheres/Carbon Nanotubes:** These are technologies in their embryonic stage with a yet uncertain future. Glass microspheres are small hollow spheres in the order of 100 um that become permeable to hydrogen when heated to 200-400 degC. The hydrogen gets trapped when the spheres are cooled to room temperature and can be released again upon reheating. Carbon nanotubes are nanometer-sized structures that work by the adsorption of hydrogen. The advantage of these new technologies is that hydrogen is stored at low pressures and therefore it is inherently safe. However, these technologies are decades away from being commercialized.

**Underground Storage:** Hydrogen, like natural gas (NG) and helium, can also be stored underground in geological reservoirs that consist of porous rock or depleted NG reserves. Underground storage of hydrogen is by far the cheapest storage technique under most situations, primarily because the “vessel” cost is very low.
Appendix-E: Diffusion of Technologies and the Logistic Curve

The logistic curve (also called S-curve due to its shape) is the most ubiquitous mathematical construct used to visually display the diffusion of technologies. All technologies that successfully diffuse into societies seem to follow the S-curve as shown in Figure A-1. While it is entirely descriptive, it is one of the most robust findings from the diffusion literature (Kemp & Rotmans, 2004). In order to illustrate its usefulness, the discussion around Figure A-1 will focus on the diffusion of single technologies. However, an advantage of the S-curve is that it allows you to analyze the diffusion of individual technologies as well as transitions of entire technological systems (Kemp & Rotmans, 2004).

The S-curve in Figure A-1 also displays 4 distinct stages or phases of the technology lifecycle - the innovation stage, take-off stage, the growth stage and the saturation stage. Most technologies rarely make it past the innovation stage which is characterized by uncertainty and a great deal of experimentation. In the next stage (take-off), is where there are signs of market acceptance either within a niche or regular markets. At this stage technical viability is of prime importance and costs are secondary. In the growth stage, after the technology has proved its utility, it starts becoming more widely accepted and a greater effort is put into lowering production costs. Standardization of the technology further aids in its acceptance and further product innovations widen the product features and scope of application. However, a distinctive feature of the S-curve model is that growth is neither linear nor unlimited.
In the final phase the market starts to saturate as growth rates slow down and improvements face diminishing returns. As a result industries experience over-capacity and try to squeeze out the last marginal cost improvements from scale economies or from outsourcing production. Often the negative effects of using the technology in large numbers begin to become apparent which can further reduce the growth rate. At the same time the saturation phase provides a ‘window of opportunity’ for a new period of experimentation and introduction of alternative technological and organizational solutions. In chapter 4 this window of opportunity is described with respect to results from empirical studies based on the diffusion of large-scale technological systems and infrastructures and their implications for future transitions.
Technology Adoption and the Bell Curve

The S-curve describes the life cycle of a technology (innovation to saturation) over time. When considering the adoption threshold of consumers over time we get another convenient figure – the bell curve or the normal distribution (Figure A-2).

(Mathematically, when this normal distribution is plotted on a cumulative density function (CDF) you get the logistic curve or S-curve.)

Figure A-2: The Bell Curve and Technology Adoption. Source (Donald, 1998)

In his classic book Diffusion of Innovations (Everett, 1995) defines diffusion as the process by which an innovation is communicated through certain communication channels over time, among the members of a social system. According to Everett, the members of this social system may be grouped into 5 categories – innovators, early adopters, early majority, late majority and laggards (Figure A-2). The adopters are

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95 It is interesting to note that most of the technological diffusion literature comprises of analyses on the temporal nature of diffusion, while spatial diffusion is rare.
differentiated based on their level of innovativeness (statistically it is the mean and standard deviation of the normal distribution that defines the boundaries between them).

The innovators and the technology enthusiasts are the ones that demand the technology and are eager to try new ideas (many of the promoters of the hydrogen futures may fall into this category). However, being an innovator also means that they have access to substantial financial resources, are capable of understanding and applying complex technical knowledge, appreciate the uncertainties and are capable of absorbing the losses in the event of an unprofitable innovation.

The early adopters also play a key role in the technology diffusion process. They are considered to be better integrated into society than the innovators and are the source of information for the vast majority. The early adopters are considered to be the ones to consult with before buying into a new technology or idea. Since the early adopters are more technology savvy than the average consumer, they also serve as a role model for the general public.

The early adopters are followed by the early majority. This group is considered to be the most pragmatic of all. They are followed by the late majority, who are conservative with respect to technology adoption. By definition the laggards are the skeptics and as such are the last to adopt any technology (Everett, 1995).

One of the main criticisms of technology diffusion and diffusion research as a whole is the problem of “pro-innovation bias” (Everett, 1995; Sarkar, 1998). This means that there is an implicit assumption that a given innovation must be adopted by all members of a
social system, should diffuse rapidly, should not be re-invented and should not be rejected. As a result of this bias we know much more about innovations that have diffused rather than those that did not, about those that diffused faster than those that diffused more gradually, about adoption rather than rejection.

A criticism of the S-curve model is that most innovations do not have an S-curve all together. S-curves only exist for innovations that become successful or somewhat successful. As mentioned earlier most innovations remain innovations and thus fail to ever cross the chasm shown in Figure A-2. The technologies we do learn about are those that succeeded, but they tend to be the exception rather than the rule. The fact that most technologies fail to cross the chasm may be attributed to the complex dynamics within the socio-technical system.

In chapter 4 we take a closer look at not just technologies but systems of technologies and their socio-technical transition dynamics with the help of the large empirical literature on the diffusion of systems of technologies and infrastructures, the theoretical literature on socio-technical transitions and the literature on the modeling of technical change. As we will see, the collective insights from these literatures offer a more sophisticated set of tools to probe the question of how to guide socio-technical change than the S-curve.