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SCENARIO AND POLICY ANALYSIS OF SUSTAINABLE ENERGY SYSTEMS AND AUTOMOBILE TRANSPORTATION

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HAL TURTON

Master of Public Policy, Australian National University, Australia
Bachelor of Advanced Science (Honours), University of New South Wales, Australia

born 22.09.1974

citizen of Australia

accepted on the recommendation of

Prof. Dr. A. Wokaun, examiner
Prof. Dr. K. Boulouchos, co-examiner
Dr. L. Barreto, co-examiner

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Abstract

Realising sustainable development over the long term is a profound challenge confronting policy and decision makers across the globe, encompassing a broad range of potentially competing goals. Within the energy sector, these competing objectives include providing access to the energy supplies needed for economic and social development while avoiding the impacts of anthropogenic climate change arising from the combustion of fossil fuels and reducing the risks of disruptions to the energy supply, among others.

Understanding these objectives and developing appropriate long-term strategies represents a significant challenge for decision makers, given both complex interactions within the energy system and major socioeconomic, political, technological and scientific uncertainties. Addressing this challenge requires appropriate policy analysis tools for studying sustainable development. With this in mind, one main theme of this dissertation is the construction and development of an integrated assessment tool for energy and climate policy and scenario analysis. The second main theme of this dissertation is the application of this analysis tool to explore sustainable development and the possible emergence of sustainable automobile transport over the 21^{st} century.

The construction of the policy analysis tool to address the first theme is delineated into different submodules. The first of these comprises developing an extended version of the "bottom-up" energy-systems ERIS (Energy Research and Investment Strategies) model, which was originally developed during the EC-sponsored TEEM and SAPIENT projects, where it was mainly used to examine issues related to the endogenisation of mechanisms of technological change. The importance of technological change as both a threat to sustainable development and a source of potential solutions guided the choice of ERIS for the work described in this dissertation, and the substantial extensions to the model. These extensions include: the implementation of a clusters approach to technology learning; the incorporation of a transportation sector with emphasis on the passenger car sub-sector; the inclusion of fuel production technologies (e.g. hydrogen, alcohols, Fischer-Tropsch liquids, etc); and the addition of emissions and marginal abatement cost curves for two main non-CO_2 greenhouse gases (methane (CH_4) and nitrous oxide (N_2O)), emissions of sulfur dioxide (SO_2), and geological and terrestrial CO_2 storage. The comprehensive coverage of almost all greenhouse gas emissions and many abatement opportunities in this extended model facilitates its linkage to the MAGICC climate model (developed by the Climate Research Unit at Norwich University), thereby ensuring that in addition to energy system detail the ERIS model is also able to represent climate change impacts and mitigation—one critical element of sustainable development.

The extended energy-system ERIS model represents one key component of the policy analysis tool developed in this dissertation. However, alone this model is somewhat limited in terms of its suitability for analysing sustainable development because, although it represents the engineering, physical and technological features of the energy system and climate in detail, it does not represent the underlying forces of economic production and consumption (nor feedbacks between the economy and energy system). Accordingly, to complement the technology-rich bottom-up energy and transport system model ERIS, a macroeconomic energy demand model and a consumer-budget transport demand model are incorporated into the policy analysis framework, with all the models linked and solved iteratively. The resulting tool—the ECLIPSE (Energy and Climate Policy and Scenario Evaluation) model—provides a detailed and flexible framework that includes many new features compared to other hybrid top-down economic and bottom-up engineering models, such as: a more disaggregated economic production function; improved calibration and parameterisation; and disaggregated modelling of passenger transport technologies and demands. The detailed modelling of transport means that ECLIPSE is particularly well-suited to analysing interactions within this sector and with the broader energy market and economy, making this framework ideal for addressing the second theme of this dissertation—to explore sustainable automobile transport.

Transport represents a significant threat to long-term sustainable development, and is one of the fastest-growing consumers of final energy and sources of greenhouse gas emissions. Moreover,

transport is heavily reliant on petroleum, a limited resource that is also associated with geopolitical risks to security of supply. The threat posed by transport (particularly road and automobile transport) to two central concerns for policy makers and elements in sustainable development—energy security and climate change—warrants a closer examination of possible pathways to a sustainable transport system.

Importantly, possible transitions in the global automobile sector over the 21st century are uncertain in terms of both technologies and energy carriers, and policy and other drivers. The uncertainty is explored in this dissertation by examining the potential role of various automobile technologies in GHG mitigation across a range of increasingly stringent abatement policies. The results provide some preliminary policy insights by illustrating the potential for advanced vehicle technologies and hydrogen to contribute to climate change mitigation, but show that fuel cell cars may be a longer-term option.

However, efforts seeking to address other elements of sustainable development are also potentially important for determining the suitability of alternative energy and transport technologies. This is explored in this dissertation in an analysis of potential synergies and trade-offs relating to security of supply and climate change. In particular, the role of a number of policy instruments in managing energy security and climate risks and stimulating technological change are examined, and the potential for policies aimed towards maintaining security of supply to promote the uptake of new technologies, reduce the cost of pursuing climate change mitigation policies, and facilitate a possible transition to a hydrogen economy are explored in detail.

Finally, the complete policy analysis framework (ECLIPSE) is applied to describe and analyse technology transitions in a scenario combining multiple sustainable development objectives over the long term, including: i) continuing economic growth, with a moderate reduction in disparities in income between different world regions; ii) maintaining a buffer of oil and gas resources to enhance security of energy supply, both globally and in vulnerable regions; iii) abating greenhouse gas emissions to ensure atmospheric CO_2 concentrations do not exceed double pre-industrial levels; and iv) ensuring global mobility demands are met, without resorting to assumptions about a large counter-trend shift to public transport or lower travel demand. The results of this analysis illustrate the technological, economic, fuel production and infrastructure implications of realising this scenario over the long term. This provides a number of policy insights by identifying critical developments required for the emergence of a sustainable global passenger transport and energy system, in terms of vehicle technologies, fuel production and broader energy system developments.

Keywords: sustainable development; climate change; energy security; technological change; hydrogen; transport; automobiles

Zusammenfassung

Nachhaltige Entwicklung über lange Zeiträume zu erreichen ist global eine große Herausforderung für Entscheidungsträger, da Nachhaltige Entwicklung eine Reihe von potentiell konkurrenzierenden Zielen umfasst. Innerhalb des Energiesektors sind dies, zum Beispiel, den Zugang zu Energieversorgung für die wirtschaftliche und soziale Entwicklung zu sichern und Risiken in der Energieversorgung zu minimieren und dabei die Auswirkungen der globalen Erwärmung, verursacht durch Verbrennung fossiler Brennstoffe, zu vermeiden.

Unter den gegebenen komplexen Zusammenhängen innerhalb eines Energiesystems und angesichts der großen sozioökonomischen, politischen, technologischen und wissenschaftlichen Ungewissheiten diese Ziele zu verstehen und eine langfristige Strategie zu entwickeln ist eine Herausforderung für Entscheidungsträger. Um diese Herausforderung der Nachhaltigen Entwicklung annehmen zu können, braucht man geeignete Analysewerkzeuge. Daher ist ein Hauptthema dieser Dissertation die Entwicklung eines integrierten Bewertungswerkzeuges für die Formulierung von Energie- und Klimastrategien und die Szenarioanalyse. Das zweite Hauptthema ist die Anwendung dieses Bewertungswerkzeuges um Nachhaltige Entwicklung und die Bedingungen für die Entstehung eines nachhaltigen Automobiltransportsystems während des 21. Jahrhunderts zu untersuchen.

Die Entwicklung des integrierten Bewertungswerkzeuges ist in verschieden Module gegliedert. Das erste Modul ist die Entwicklung einer erweiterten Version des „bottom-up“ Energiesystemmodells ERIS (Energy Research and Investment Strategies). Das Modell wurde ursprünglich im Rahmen der EU-Projekte TEEM und SAPIENT entwickelt, um die Endogenisierung von Mechanismen des technologischen Fortschritts zu untersuchen. Die Bedeutung von technischem Fortschritt sowohl als Bedrohung der Nachhaltigen Entwicklung als auch als Quelle von möglichen Lösungen führte zur Auswahl von ERIS als Bewertungswerkzeug für diese Dissertation und zu dessen substantieller Erweiterung. Diese Erweiterung inkludiert: Implementierung des “Cluster”-Zugangs für technologisches Lernen; die Inkorporation des Transportsektors mit Betonung des Automobiltransportsektors; die Einbeziehung von Treibstoffproduktionstechnologien (Wasserstoff, Alkohole, Fischer-Tropsch Treibstoffe, usw.); und die Einfügung von Emissionswerten und marginalen Minderungskosten für die zwei wichtigsten Treibhausgase (Methan (CH_4) und Lachgas (N_2O)) neben dem CO_2, von Emissionswerten für Schwefeldioxid (SO_2), und die Abbildung von geologischen und terrestrischen CO_2-Speichern. Die Abdeckung von fast allen Treibhausgasen und vielen Minderungs-Optionen im erweiterten ERIS-Modell ermöglicht seine Verknüpfung mit dem Klima-Modell MAGICC (entwickelt an der Climate Research Unit der Norwich University). Dies ermöglicht, dass ERIS neben der detaillierten Beschreibung des Energiesystems auch Minderungsstrategien zur Reduktion des Schadens durch Klimaveränderung beschreiben kann — ein kritisches Element von Nachhaltiger Entwicklung.

Das erweiterte ERIS-Modell ist eine Schlüsselkomponente des Bewertungswerkzeuges, das in dieser Dissertation entwickelt wurde. Trotz dieser Erweiterung ist das Modell, für sich genommen, nur begrenzt zur Analyse Nachhaltiger Entwicklung nutzbar. Obwohl es nämlich die technischen und physikalischen Eigenschaften des Energiesystems und des Klimas im Detail abbildet, kann es weder die zugrunde liegenden Kräfte der ökonomischen Produktion und des Konsums beschreiben noch Rückkoppelungen zwischen der Gesamtwirtschaft und dem Energiesystem. Daher wird das Technologien betonende „bottom-up“ Energie- und Transport-Modell ERIS durch ein makroökonomisches Energienachfragemodell und ein Transportmodell (einschließlich Budget-Beschränkungen der Konsumenten) ergänzt. Das Ergebnis davon ist eine integriertes Bewertungswerkzeug, in dem alle erwähnten Modelle verknüpft sind und für das der Name ECLIPSE (Energy and Climate Policy and Scenario Evaluation) gewählt wurde. ECLIPSE stellt somit ein detailliertes und flexibles Gerüst dar, das – im Vergleich zu anderen Kombinationen von „top-down“-Wirtschafts- mit „bottom-up“ technischen Modellen viele neue Fähigkeiten hat. Diese inkludieren: eine mehr disaggregierte ökonomische Produktionsfunktion; verbesserte Kalibrierung und Parametrisierung; und disaggregierte Modellierung von Personenverkehrtechnologien und der Nachfrage nach Transportleistung. Die detaillierte Modellierung des Transports bedeutet, dass ECLIPSE besonders gut geeignet ist, um Interaktionen zwischen diesem Sektor und dem restlichen

Energiemarkt und der Wirtschaft zu analysieren. Es ist daher ideal dazu geeignet, ein nachhaltiges automobiles Transportsystem zu erforschen.

Die Auswirkungen des Transportsystems stellen eine signifikante Bedrohung der langfristigen Nachhaltigen Entwicklung dar. Insbesondere ist der Verkehrssektor einer der am schnellsten wachsenden Energieverbraucher und Quellen von Treibhausgasemissionen. Darüber hinaus hängt das Transportsystem stark vom Erdöl ab, dessen Ressourcen nur beschränkt verfügbar und außerdem mit geopolitischen Risiken verknüpft sind. Die Gefährdung zweier zentraler Punkte der Nachhaltigen Entwicklung — Energiesicherheit und Klimawandel — durch das Transportsystem (im speziellen Straßenverkehr und Automobilverkehr) macht eine genauere Untersuchung von möglichen Wegen zu einem nachhaltigen Transportsystem lohnend.

Wichtig ist dabei, dass mögliche Übergänge im globalen Automobilsektor während des 21. Jahrhunderts sowohl betreffend der Technologien und Energieträger als auch bezüglich des politischen Umfelds und anderer Rahmenbedingungen mit signifikanten Unsicherheiten behaftet sind. Diese Unsicherheit wird in dieser Dissertation analysiert indem der Einfluss verschiedener Automobiltechnologien auf die Vermeidung von Treibhausgasemissionen unter einer Reihe von immer strengeren Emissionsbestimmungen untersucht wird. Erste Resultate der Untersuchung quantifizieren das Potential für fortgeschrittene Fahrzeugtechnologien und für Wasserstoff bei der Verminderung des Klimawandels. Es ergibt sich daher, dass Brennstoffzellenautos eine langfristige Option für die weltweite Klimapolitik sind.

Nichtsdestoweniger sind Bemühungen, die andere Elemente der Nachhaltigen Entwicklung untersuchen, auch für die Bestimmung alternativer Energie- und Verkehrstechnologien wichtig. Dem wird in dieser Dissertation Rechnung getragen indem der funktionelle Zusammenhang zwischen Versorgungssicherheit und Klimawandel analysiert werden. Im speziellen werden im Detail eine Reihe von Maßnahmen untersucht, die gleichzeitig auf Versorgungssicherheit, Reduzierung der Klimarisiken und Kosten der Klimapolitik, auf die Stimulierung von technologischem Wandel und auf den Aufbau einer Wasserstoffwirtschaft abzielen.

Schließlich, wird das komplette integrierte Bewertungswerkzeug ECLIPSE angewandt, um einen technologischen Wandel zu beschreiben und mit Hilfe eines Szenarios zu analysieren. Das resultierende Szenario vereint mehrere Ziele der langfristigen nachhaltigen Entwicklung miteinander: i) weiteres ökonomisches Wachstum, mit einer moderaten Reduktion der Einkommensungleichheit zwischen verschiedenen Weltregionen; ii) Aufrechterhalten eines Puffers von Erdöl- und Gasressourcen um die Versorgungssicherheit mit Energie global und in kritischen Regionen zu verstärken; iii) Begrenzung von Treibhausgasemissionen um sicherzustellen, dass die atmosphärische CO_2-Konzentration das Doppelte der vor der „Industriellen Revolution“ vorherrschenden Werte nicht übersteigt; und iv) Gewährleistung, dass die globale Mobilitätsnachfrage befriedigt wird, ohne auf Annahmen zurückgreifen zu müssen, die einen starken Gegentrend zum öffentlichen Verkehr oder eine niedrigere Mobilitätsnachfrage annehmen. Die Resultate dieser Analyse illustrieren die technologischen, ökonomischen, Treibstoffproduktions- und Infrastrukturimplikationen einer Realisierung dieses Szenarios über lange Zeithorizonte (bis zum Jahr 2100). Für die politischen Entscheidungsträger relevant ist, dass mit diesem Szenario Entwicklungen identifiziert werden, die für das Entstehen eines nachhaltigen globalen Personenverkehrs und Energiesystems nötig sind. Diese Entwicklungen — und der damit verbundene Handlungsbedarf — beziehen sich auf Fahrzeugtechnologien, Treibstoffproduktion und allgemeine Energiesystementwicklungen.

Stichwörter: Nachhaltige Entwicklung, Klimawandel, Energiesicherheit, technologischer Wandel, Wasserstoff, Verkehr, Autos

Chapter 1. Introduction and organisation

Decision makers in governments around the world are confronted by an array of complex challenges as they endeavour to predict the impact of existing and prospective policies on future social, economic and environmental well-being. The ability to estimate accurately the impact of a given policy is essential since it increases the likelihood that the most suitable policy instruments are chosen and applied, assisting governments in allocating their and society's scarce resources in the most effective and efficient manner.

Among the challenges facing policy makers this century, the most significant may relate to realising the goals of sustainable development, whereby the needs of current generations are met without compromising the ability of future generations to meet their own needs. Within the spectrum of issues encompassed by sustainable development, one of the most demanding aspects may well be responding to anthropogenic climate change by reducing greenhouse gas (GHG) emissions (see, for example, IPCC 2001a,b,c).

Many proposed policy responses to climate change are targeted towards major sources of anthropogenic emissions, including stationary energy use and transportation, but such policies also have major implications for other economic sectors, both directly and because of other more complex energy-economy interactions. Moreover, climate change mitigation is only one of the challenges of sustainable development confronting policy-makers, and formulating an appropriate response is confounded by uncertainty regarding, among others, how future global economic activity and energy and transport demand will unfold. The impact of the pervasive and ubiquitous process of technological change on both economic development and specific technologies (Maddison 1993; McDonald and Schrattenholzer 2001), the possible emergence of a sustainable global energy system or hydrogen economy (Barreto *et al.* 2003), and the possibility of economic "catch-up" by less developed world regions also all potentially have major implications for energy and transport demand and the effectiveness of policy intervention. The reemergence of concerns about the security of the energy supply reflects another significant uncertainty affecting the future energy and transport systems. To cope with these uncertainties, effective policy-making requires flexible integrated assessment tools that can assess a range of scenarios and evaluate the impact of different policies, including those for climate change mitigation.

One central theme and aim of this dissertation is to construct a comprehensive and flexible global policy analysis tool for investigating the impact of future scenarios and policy measures on sustainable development, including the impact on indicators of climate change (such as global average temperature and sea-level), energy and transport system characteristics and economic variables. The policy analysis tool outlined here seeks to integrate scenario specification through to climate impacts, and includes a number of linked modules. The main model elements comprise a macroeconomic (top-down) model and a simple travel demand model linked to an energy systems and GHG abatement (bottom-up) model and a climate model. This framework integrates macroeconomic activity with energy and transport system technology detail, including a range of GHG abatement options. However, it should be made clear at this early stage that the aim of this dissertation is not to create another detailed general equilibrium economic model (such as EPPA—see Babiker *et al.* 2001), or a highly detailed energy system model (such as MESSAGE—Messner and Strubegger 1994; 1995), but instead to develop an integrated and comprehensive, yet flexible analysis system.

The specific advantages of such an analysis tool, compared to many existing models, relate to the inclusion of a comprehensive set of abatement and technology options whilst maintaining the simplicity and flexibility to analyse a large number of scenarios and sensitivities relatively easily. The flexibility of this tool may be useful for examining the consistency with which particular trends in future energy system characteristics arise under a diverse range of plausible future scenarios and assumptions.

Although this climate policy and scenario analysis tool is designed to be applicable to the analysis of a wide range of policies and instruments, here its capabilities are demonstrated by exploring the possible emergence of a global sustainable automobile transport system over the 21st century, encompassing sustainable greenhouse gas emissions, long-term security of energy supply, and economic development. This analysis represents the second main theme of this dissertation.

Transport is selected as a focus of the dissertation because it represents a significant policy challenge, particularly in the context of long-term sustainability. Today's transport system, especially private automobile transport, is highly dependent on petroleum fuels, and therefore is vulnerable to threats to the security of the energy supply and contributes to greenhouse gas emissions. In addition, use of current transport technologies accounts for a large and increasing share of local air pollution. However, the most substantial challenges arising from transport over the 21st century are likely to emerge as a consequence of economic development in today's developing countries, leading to increasing demands for personal mobility. In addition to addressing a significant policy challenge, by focusing on transport this dissertation also helps to fill an important gap in the scenario and energy analysis literature, which often treats transport in a very stylised and aggregated way, or fails to consider the interaction between the transport and energy systems (although recent exceptions exist, such as Schafer and Jacoby 2005).

To maintain overall consistency and focus, the aim of exploring the emergence of a global sustainable automobile system also guides the presentation of the development and application of the policy analysis tool in this dissertation. Specifically, at various stages in the development of the policy analysis tool, the dissertation analyses different aspects of: future transport technology market penetration; synergies between different elements of sustainable development; and, the macroeconomic and transport sector consequences of achieving climate change mitigation targets, before culminating in the description and analysis of a sustainable transport scenario. In this way the two main themes of the dissertation—developing an integrated policy analysis tool, and exploring the emergence of a global sustainable transport system—are brought together.

Turning to the organisation of the remainder of this document, the dissertation is delineated into five main separate analyses, which can be classified as either predominantly methodological or policy analytical, although there is some overlap. The overall organisation is illustrated in Figure 1-1. Following Chapter 2, which outlines the main issues motivating this dissertation, the first of the separate analyses (presented in Chapter 3) is purely methodological and describes the development of the bottom-up energy system model used in the integrated policy analysis tool, and the construction of a suitable scenario for exploring sustainable development. Chapter 3 presents how an existing electricity system model (the ERIS model of Kypreos *et al.* 2000; Barreto and Kypreos 2000) was substantially expanded and reorganised to incorporate additional energy sectors, a detailed mix of electric, non-electric stationary (including heat) and transport technologies; technology learning; and a comprehensive set of greenhouse gas abatement options, sinks and sources. The inclusion of almost all anthropogenic sources of greenhouse gas emissions also facilitated the soft-linking to the simple climate model MAGICC (TAR version) (Wigley 2000; Hulme *et al.* 2000). Much of the work in Chapter 3 was published in Turton and Barreto (2004) and partly in Turton and Barreto (2005).

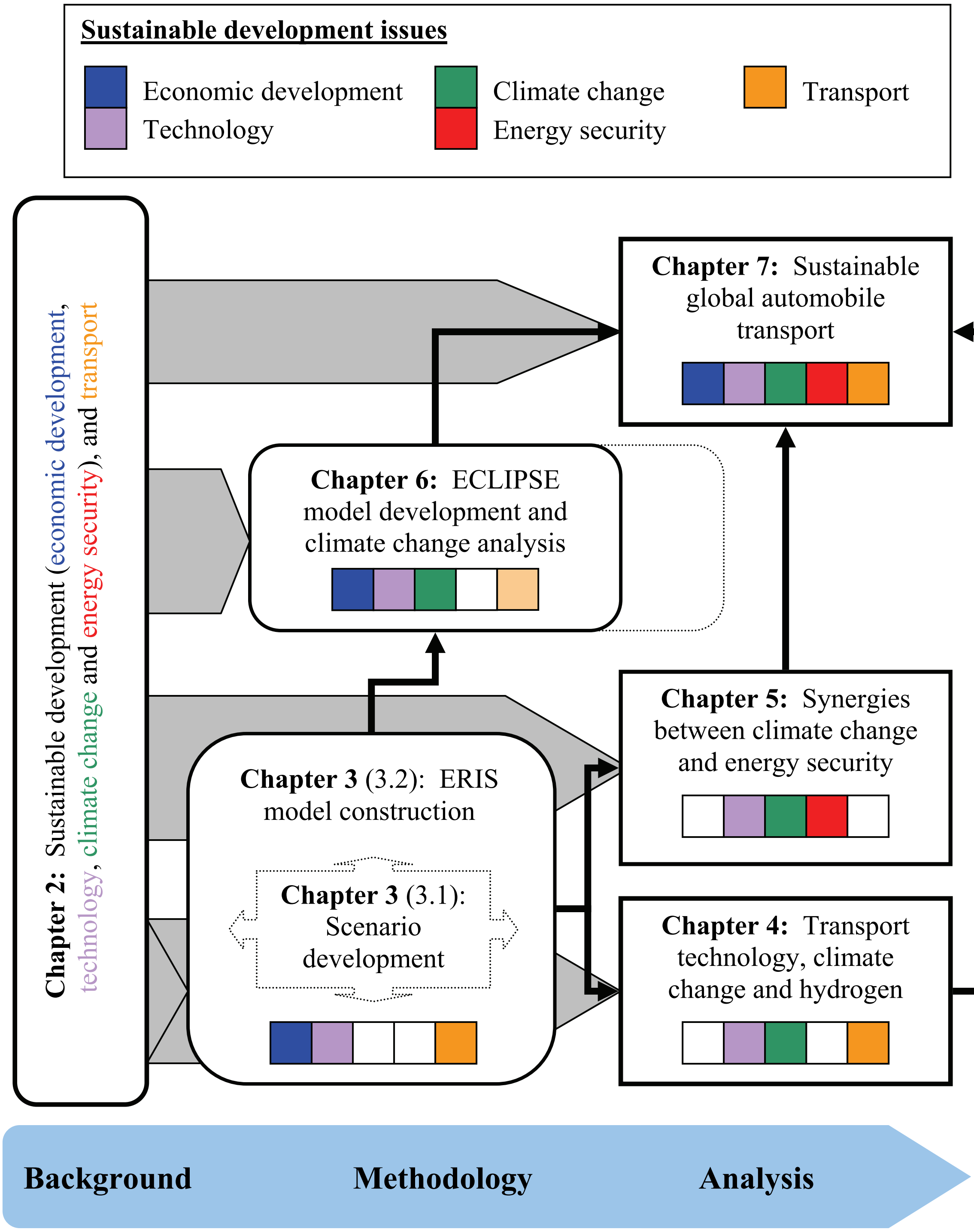

Figure 1-1 Dissertation organisation, issues and chapter linkages

Given the objective of exploring sustainable automobile transport, the second analysis (in Chapter 4) applies the energy-climate model presented in Chapter 3 to investigate the role of new automobile technologies and fuels (specifically, hydrogen) in climate change mitigation. This analysis has been published in Turton and Barreto (2005). These first two analyses alone illustrate some of the potential implications for transport technology and fuel choice of growing demand, climate change policies and limited resource availability. However, sustainable development (in the context of sustainable transport) goes beyond climate change mitigation, and hence it is also important to understand other features of a sustainable energy system. One critical requirement for long-term sustainable development is access to secure sources of energy, and Chapter 5 in this dissertation explores potential synergies and trade-offs between policies aimed at maintaining energy security and mitigating climate change—two central elements of energy and transport sustainability. This work is published in Turton and Barreto (2006).

Following the analysis of energy security and climate change, the dissertation returns to the development of the methodological framework, and presents the final stage in constructing the integrated policy analysis tool—the ECLIPSE (Energy and Climate Policy and Scenario Evaluation) model—in Chapter 6. This chapter describes the linkage of the energy system model (developed in Chapter 3, and applied in Chapters 4 and 5) to macroeconomic and transport models so as to incorporate the impact of energy costs on economic activity. Changes in economic activity, in turn, affect demand for different forms of final energy (such as electricity, low-quality thermal, high-quality thermal) and transport (passenger vehicle, air, and other comprising mainly land and sea freight), and this analysis describes the soft-linking and iterative solution of the macroeconomic and energy models. This chapter also examines potential advantages of this integrated modelling approach compared to the stand-alone ERIS model, particularly in terms of technology dynamics. Consistent with the second theme of this dissertation to explore a sustainable automobile transport scenario, we also present in this chapter the application of the integrated tool to assess the economic impact of a series of climate change mitigation policies aimed at achieving a range of atmospheric carbon dioxide (CO_2) concentration targets. The impact on the energy and transport system of one of these policy targets—550 parts per million volume (ppmv)—is presented in detail. This integrated model development has been submitted for publication (Turton 2005a).

The fifth and final analysis in the dissertation, in Chapter 7 combines many of the elements in Chapters 3 to 6, and applies the fully integrated policy analysis tool to develop a scenario of global sustainable automobile transport over the 21st century. This scenario features elements of sustainable development including: continuing global economic growth, with some economic catch-up by less developed world regions; increasing demands for personal mobility; maintenance of global and regional security of energy supply; and climate change mitigation by limiting atmospheric CO_2 concentration to below 550 ppmv. Although stabilising atmospheric concentrations to a lower level could be expected to further reduce the risk of climate change, 550 ppmv has been selected as a target for sustainable development that is achievable, without unanticipated technology breakthroughs, given that current atmospheric concentrations are already approaching 380 ppmv (see Figure 2-3 in the following chapter). The analysis in Chapter 7 describes the main energy and transport technology developments required to realise this scenario, with the overall objective of identifying potential targets for policy support. Accordingly, this chapter represents the culmination of the work in Chapters 3 to 6, and therefore the findings and insights discussed therein represent some of the main overall findings of this dissertation, in terms of sustainable automobility. Some parts of Chapter 7 have been submitted for publication (Turton 2006a).

Each of the five main analyses briefly introduced above is somewhat independent and, accordingly, specific background, aims, and some methodological details are presented separately for each (although many common methodological features are described in Chapter 3 and Chapter 6). Furthermore, the results of each analysis (where appropriate) are also discussed separately. This allows the reader to understand and appreciate the main implications of each analysis without necessarily needing to read the entire dissertation. Nevertheless, the dissertation also includes a general introduction (presented in the proceeding Chapter 2) which outlines the challenge of achieving sustainable development, the implications for climate change, and the threats posed by the transport sector, and a synthesis of the key conclusions related to the overall thematic aims (Chapter 8).

Chapter 2. Transport, technology, sustainable development and climate change

The concept of sustainable development has evolved into a guiding principle for a livable future world in which human needs are met without compromising the ability of future generations to meet their own needs (Brundtland Report 1987). One of the implications of the pursuit of sustainable development is that the natural systems that support present and future needs must be maintained. However, addressing the challenge of sustainability encompasses other social, economic and environmental dimensions, and requires a long-term systematic perspective and the integration of many different elements. Energy and transport are two such elements, and directing the global energy and transport systems onto a sustainable path is becoming an increasingly important concern and policy objective (Schrattenholzer *et al.* 2004; IEA 2001a; Riahi *et al*. 2001; Barreto *et al.* 2003).

Realising sustainable energy and transport systems as part of achieving overall sustainable development requires overcoming a number of challenges in terms of delivering affordable, secure and clean energy for poverty alleviation and ongoing development throughout the world. Within this context, some of the most significant threats to sustainable energy development confronting policy makers relate to climate change, security of energy supply and economic development. Two of these challenges—mitigating the impacts of climate change and maintaining security of energy supply—are prominent issues on both national and international policy-making agendas.

The increasing evidence of human-induced interference with the Earth's climate system and mounting concern about potentially serious future adverse impacts make global climate change one of the most significant challenges to the realisation of sustainable development in the long term (IPCC 2001a,b). Efforts to address climate change necessitate a focus on global energy and transport systems, which represent the major source of anthropogenic greenhouse gas emissions.

Security of energy supply, in comparison, is often considered a more pressing short-term concern and threat to development by policy makers. An excessive reliance on certain fossil fuels, oil and natural gas in particular, is an issue of concern because it potentially creates economic, physical and geopolitical risks (EC 2001). Specifically, the current overall dependence of OECD countries on oil supply from politically volatile regions and the definition of appropriate responses to potential supply disruptions remain challenging issues (e.g., DOC 1999; EC 2001; IEA 2001b). Realising sustainable energy and transport systems with a low impact on the global climate, whilst maintaining access to secure and affordable supplies of energy for development may require profound and wide-reaching changes.

One objective of this dissertation is to analyse these changes in terms of the potential to establish a sustainable global transport system as part of the realisation of a sustainable global energy system and other goals of sustainable development, including climate change mitigation, maintaining secure access to affordable supplies of energy, and continuing economic development, including reducing the divergence between rich and poor world regions. Envisioning and understanding how the long-term future global energy and transport systems can meet increasingly stringent requirements in a sustainable way is an important element for designing policy responses that will promote the transition to a sustainable future. However, there are significant social, economic, environmental, technological and political uncertainties that may influence energy system development, meaning that many alternative sustainable energy pathways may emerge.

This dissertation examines the technologies and energy carriers that could play a role in these pathways to sustainable development, including their potential, market opportunities and the barriers they could face as well as the conditions and policy actions necessary for their successful diffusion (Williams *et al.* 2000). Since the evolution of transport and energy systems is slow and may span decades or sometimes even centuries, the emergence of a sustainable global energy and transport system is likely to be a gradual long-term process requiring profound transformations from current infrastructure and technologies to new systems and structures. This highlights the need to take a very long-term perspective both in terms of studying the potential to realise a sustainable transport system, and also when formulating policy responses aimed at securing sustainable development. Moreover, energy and transport systems are complex combinations of technologies and fuels, both complementary and competing, and understanding how these sub-components may interact in the future is non-trivial. Accordingly, understanding the possible emergence of a sustainable energy system, and formulating policy responses requires appropriate analytical approaches and tools.

With this in mind, this dissertation addresses this need for analytical tools that capture energy system detail and are capable of providing a suitable long-term perspective; and investigates how a possible transition to a transport and energy system compatible with the broader goals of sustainable development could unfold, with the aim of identifying potential technology targets for government policy support and intervention. Importantly, energy and transport systems are faced with unique and substantial challenges in realising the goals of sustainable development, particularly in terms of avoiding serious consequences of climate change and reducing dependence on scarce resources. The major elements in energy sustainability and transport sustainability are discussed below, and summarised in Box 2-1.

2.1 Major elements in energy sustainability

Two fundamental challenges confronting the international community in the 21st century are the eradication of poverty and realisation of sustainable development. Addressing these interrelated challenges requires a long-term systematic perspective and the integration of a range of potentially competing social, economic and environmental requirements.

Cutting across all of these dimensions is the vital role of energy in development and poverty alleviation. Access to energy services and energy technologies is essential for supporting many of the systems that maintain human well-being—energy is directly implicated in food production and distribution, providing access to water, education and health services, in addition to basic services such as heating and cooking, all of which are fundamental to overcoming poverty. Energy is also essential for further sustainable development, beyond merely satisfying the most basic human needs, including providing mobility and sustaining wealth-creating industries. Accordingly, a first-order requirement for development is ensuring access to secure and affordable sources of energy (and energy services). Figure 2-1 illustrates the relationship between energy consumption and economic activity across 168 countries for the year 2000, and Figure 2-2 shows how a similar relationship is maintained across time for a number of selected countries or regions.

However, providing energy for development goals poses a number of challenges, and one of the most significant is the need to ensure that satisfying human requirements does not itself compromise the natural systems upon which human well-being depends. Some of the implications of energy's role in development, and the threat posed to the global climate arising from increasing energy demand are discussed in the following section.

Box 2-1 Sustainable development in the context of energy and transport

Despite wide usage of the term, and a broad consensus of the general concept of sustainability, interpretations vary in terms of implementation given the wide range of potentially competing objectives encompassed by sustainable development. Accordingly, it is essential to be clear about what is meant by sustainable development, particularly in relation to the energy system, and how this is operationalised in subsequent chapters of this dissertation.

The definition adopted here consists of a number of qualitative targets, which are quantified for the specific analyses presented in proceeding chapters. The qualitative criteria cover economic, resource and environmental sustainability, in addition to inter- and intra-generational aspects of social equity (*Klaassen et al.* 2002).

Sustainable development policy objectives particularly relevant to the energy and transport sectors include:

I. core social and economic aims, such as
   a. maintaining economic growth (in terms of GDP/capita),
   b. reducing socioeconomic inequity among world regions (that is, differences in relative GDP per capita), and
   c. satisfying human needs for personal mobility; and
II. objectives related to reducing specific environmental impacts in which energy is directly implicated, or avoiding resource depletion, including
   a. mitigating long-term environmental stress arising from anthropogenic climate change, by reducing GHG emissions,
   b. maintaining access to secure and affordable sources of energy needed for development (and poverty alleviation), including ensuring that exploitation of exhaustible primary energy carriers is undertaken in a way that avoids supply disruptions, and
   c. reducing acidification, tropospheric ozone production, and other emissions from fuel combustion.

Other elements of sustainable development, which go beyond the energy system (although may still be related), are not dealt with explicitly in this dissertation. These include the reduction of long-term environmental impacts related to land use (e.g., deforestation, desertification, eutrophication), stratospheric ozone depletion, loss of biodiversity, and human and ecological toxicity.

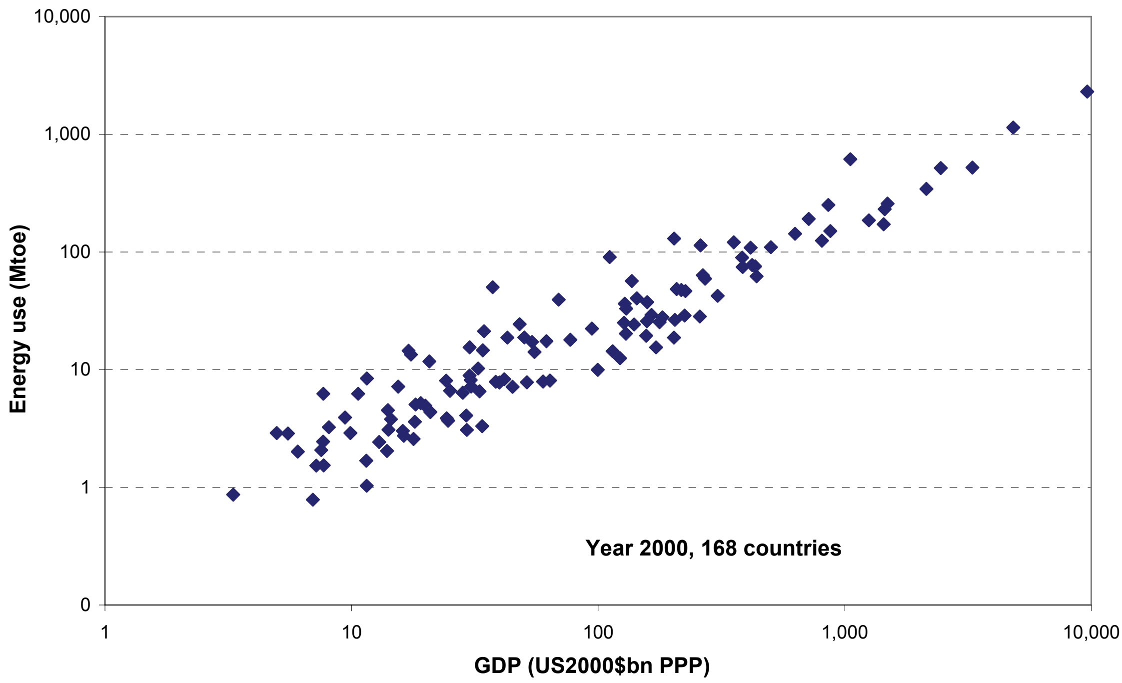

Figure 2-1 Relationship between country energy consumption and economic output, 2000

Source: World Bank 2005

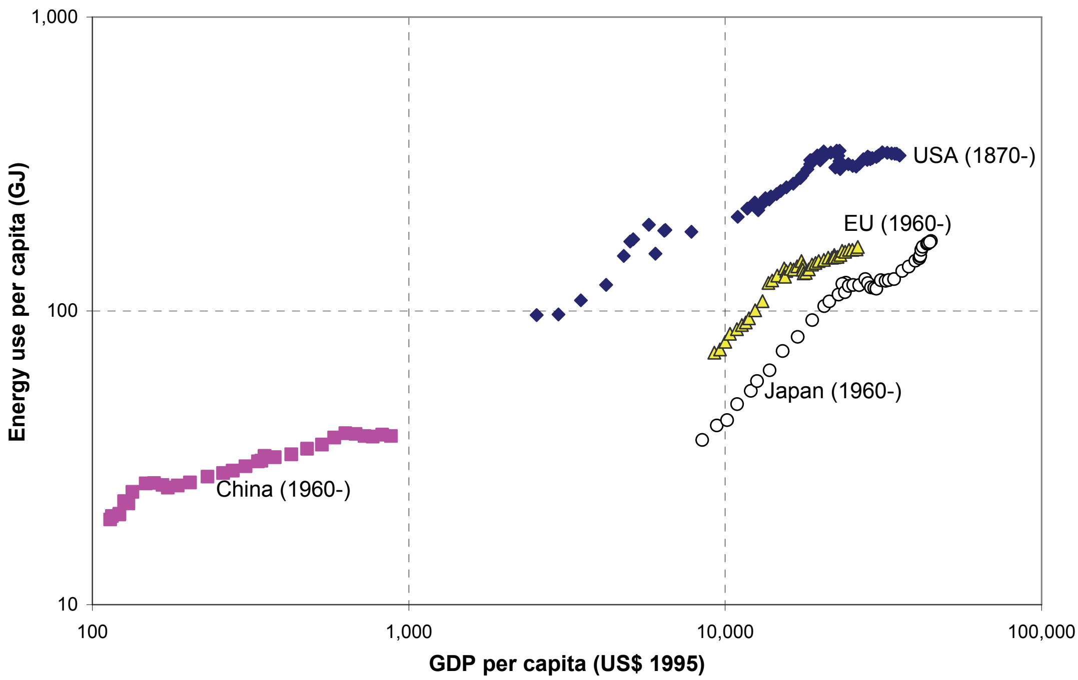

Figure 2-2 Historical relationship between energy consumption and income for selected countries

Source: IEA 2003a; IEA 2003b; IEA 2003c; IEA 2003d; EIA 2005; BEA 2005; Maddison 1993

2.1.1 Climate change and sustainable development

Among the challenges to long-term sustainability, including energy sustainability, climate change constitutes perhaps the most serious. Emissions of greenhouse gases (GHGs) from human activities are leading to changes in the composition of the global atmosphere. This is illustrated in Figure 2-3 for emissions and concentrations of carbon dioxide (CO_2)—one of the most important greenhouse gases—from combustion of fossil fuels,[1] which have been increasing almost continuously since the industrial revolution. These changes in atmospheric concentration are already leading to changes in climate (IPCC 2001a,b), and depending on future emissions and other uncertain factors, may result in significant changes to global climate (for an illustration of the range of possible impacts on temperature, see Figure 2-4). This is likely to result in a range of impacts on many physical, biological and ultimately human systems, including agricultural productivity, health, biodiversity, precipitation, and flood risk, to name but a few (see IPCC 2001b for a more comprehensive description of possible impacts). The impact of climate change on these systems is likely to be wide-scale, long-term, and in many cases irreversible, with the possibility of very dramatic and unpredictable changes (IPCC 2001b). Anthropogenic climate change affects many of the systems upon which human welfare depends and this represents one of the most serious challenges to achieving sustainable development.

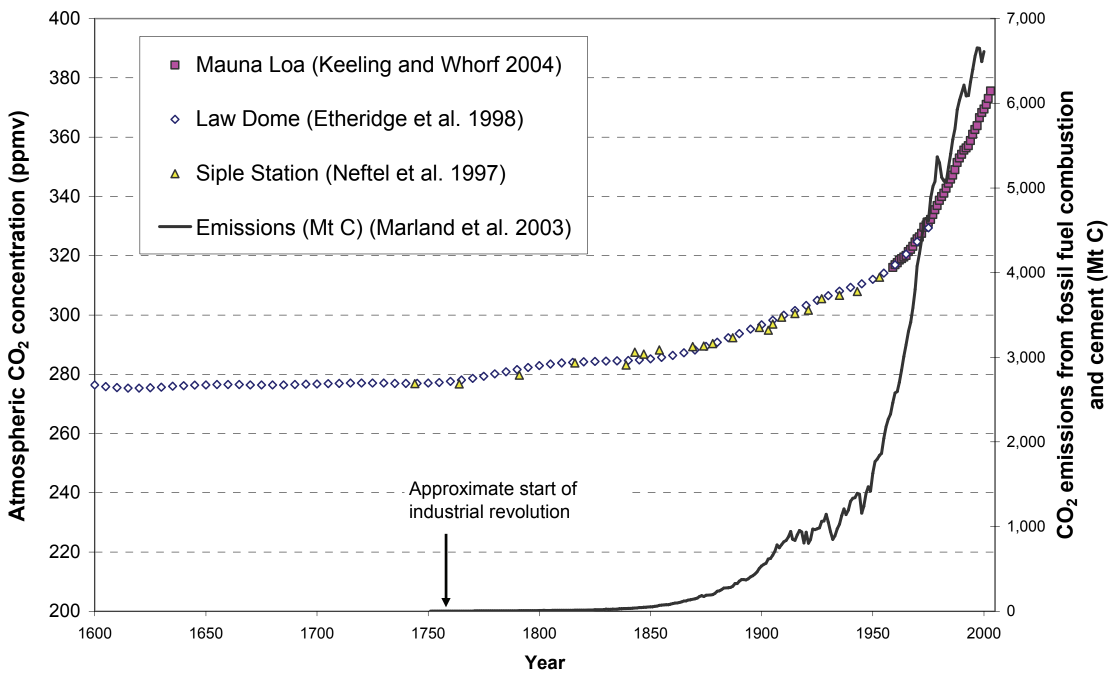

Figure 2-3 Historical atmospheric CO_2 concentrations and emissions from fossil fuel combustion

[1] We use the term fossil fuels throughout to refer to carbon fuels of geological origin, including coal, gas and oil. However, this term may not be entirely correct since there is some evidence that some geological stores of carbon fuels are of abiogenic origin (see summary in Odell 2004, Chapter 6).

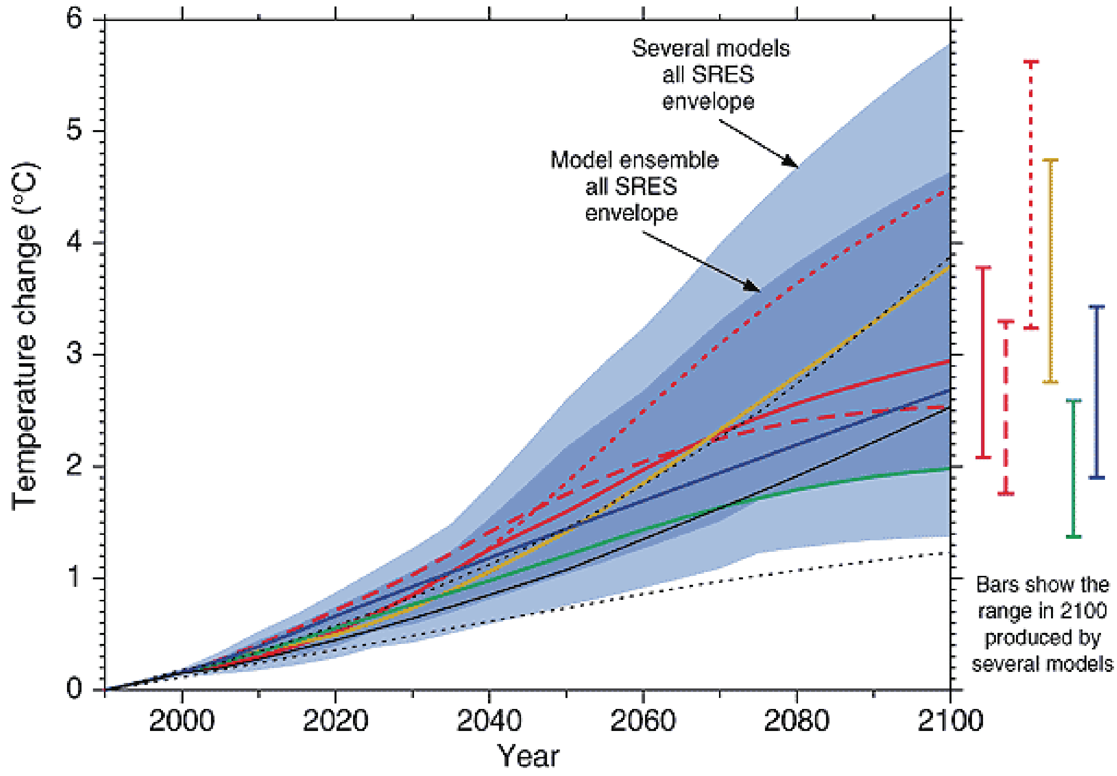

Figure 2-4 Range of future temperature scenarios from IPCC, relative to 1990

Note: SRES refers to the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart 2000).

Source: IPCC 2001d

The increase in emissions of GHGs has generally been a result of the effect a number of demographic, economic, technological, resource and policy drivers. This can be illustrated by decomposing emissions from energy use into some of the key driving variables, based on the IPAT identity (where Impact = Population x Affluence x Technology) (Ehrlich and Holdren 1971). For instance, carbon dioxide (CO_2) emissions can be represented by the following decomposition formula:

$$CO_2 = Pop \bullet \frac{GDP}{Pop} \bullet \frac{Energy}{GDP} \bullet \frac{CO_2}{Energy} \quad (2\text{-}1)$$

Here, the impact on CO_2 emissions is a function of population (*Pop*), per capita incomes (or affluence) (*GDP/Pop*), and two factors representing technology—the amount of energy required to produce a unit of GDP (*Energy/GDP*) which depends on economic structure and end-use and conversion technologies; and the carbon intensity of the energy source ($CO_2/Energy$), which depends largely on energy production technology and fuel choice. As presented in Figure 2-1 and Figure 2-2, there is a strong relationship between income and energy consumption and, all other things being equal, an increase in population or affluence will lead to an increase in energy use and emissions. Of course, the relationship presented in the decomposition equation is highly aggregated and one needs to remember that changes in consumption and economic production structure are likely to accompany changes in incomes (Hamilton and Turton 2002). However, it provides a useful guide to the core driving forces. One additional and critical driving force is policy, which influences all of the elements in the IPAT formula. Accordingly, policy can play a potentially major role in curtailing greenhouse gas emissions.

Looking at historical data, it is clear that the growth in greenhouse gas emissions from energy consumption has usually accompanied economic development and expansion (i.e., the combined impact of population and per capita income growth), and Figure 2-5 shows how emissions and global GDP have developed since the early 1970s. However, Figure 2-5 also partly illustrates a slow "decoupling" of economic growth and greenhouse gas emissions, with the global economy in 2000 being roughly 35-40 percent less carbon-intensive than in the early 1970s, largely as a result of technological development and a shift from emissions-intensive manufacturing to less emissions-intensive services (i.e., changes in the technology elements in the formula above). This development offers some hope for achieving the goals of sustainability, and highlights the potentially important role of technology, although a simple extrapolation of historical technology trends is far from sufficient to achieve sustainable development.

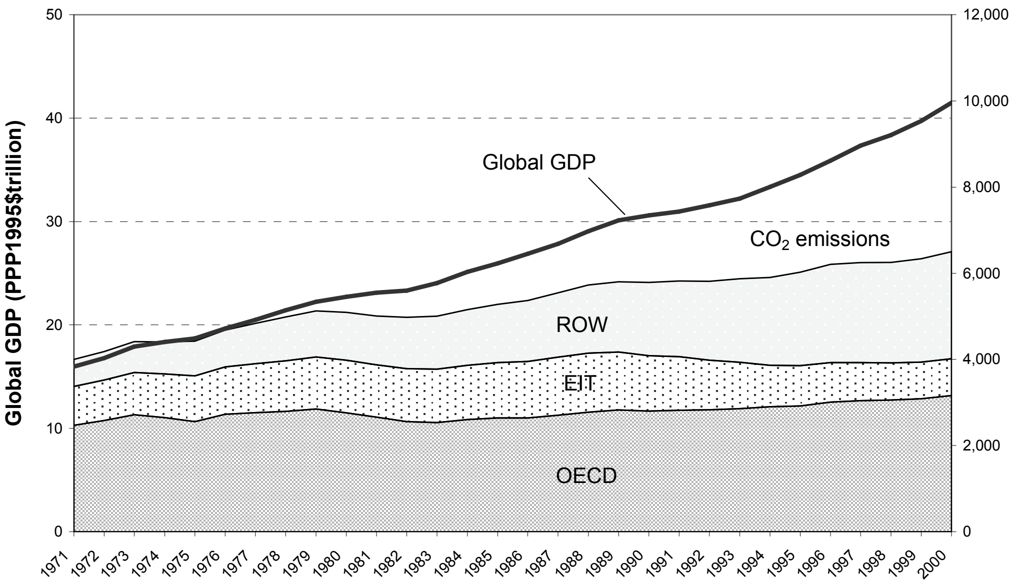

Figure 2-5 Global CO_2 emissions from energy, 1971-2000

Source: IEA 2003a; IEA 2003b; IEA 2003c; IEA 2003d

Figure 2-5 also partly shows how developed countries (OECD[2] and economies in transition (EITs)) have historically been responsible for most emissions of CO_2, and developing regions constituting the rest of the world (ROW) are only now beginning to achieve comparable aggregate emissions (while their per capita emissions remain much lower). Looking more closely at the contribution of different world regions, Figure 2-6 plots regional per capita income against per capita CO_2 emissions from fossil fuel combustion for 11 major world regions. The relative population of each world region is represented in Figure 2-6 by the area of the circle surrounding each data point. On this regional level there is a relatively strong correlation between per capita income and per capita emissions (as predicted by the IPAT identity and implied in Figure 2-6), although some regions are clearly more or less carbon intensive. On the other hand, population and greenhouse gas emissions are relatively unrelated, and around 15 percent of the world's population is responsible for almost half of

[2] The definition of OECD used here includes only those countries who members of the Organisation in 1990, and therefore excludes more recent entrants such as Mexico, South Korea, Poland, the Czech Republic, Hungary and Slovakia.

global emissions. One of the most significant challenges facing the global energy system and climate in the future is the conflict between the potential impact on energy use and greenhouse gas emissions of economic development in developing countries, on the one hand, and the economically and socially desirable goal that they achieve levels of prosperity similar to those existing in industrialised countries today, on the other.

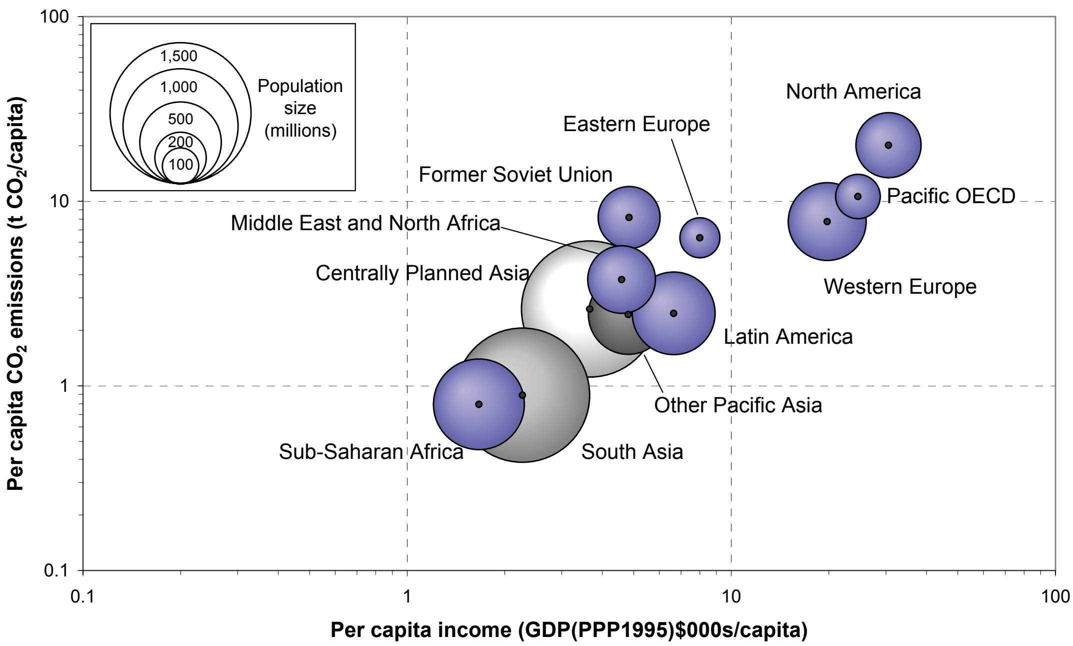

Figure 2-6 Per capita emissions, per capita income and population, 2000

Source: IEA 2003a; IEA 2003b; IEA 2003c; IEA 2003d; UN 2004

Importantly, future development raises challenges not only related to climate change mitigation, and providing access to the affordable and secure sources of energy required to achieve long-term economic growth may itself be particularly demanding, given the uneven distribution of conventional energy resources. This is explored briefly in the following section.

2.1.2 Energy security and sustainable development

Security of the energy supply has recently re-emerged as a focus of government policy intervention throughout much of the world, driven partly by geopolitical developments, and in some cases by the impact of supply shortages caused by domestic market, institutional and regulatory failures (such as in California in 2000). The current overall dependence of OECD countries on oil supplied from politically-volatile regions and the definition of appropriate responses to potential supply disruptions remain challenging policy issues (e.g. EC 2001; IEA 2001b; DOC 1999).

Renewed concern regarding security of energy supply is also partly a consequence of the realisation that future economic development and poverty alleviation in today's less developed regions will place significant pressure on global energy resources over the next century (Odell 2004; IEA 2004; EIA 2004). Increasing demand for limited resources, which are unevenly distributed geographically, may expose an increasing number of countries and people, and proportion of global economic activity, to potential threats to supply security. This will be compounded by depletion and eventual exhaustion of global oil and gas resources, although this in itself will probably manifest as a gradual process rather than an unpredictable supply disruption, since increasing scarcity should improve the commercial viability of less economic reserves, spur additional exploration, promote technological innovation and encourage conservation. However, access to abundant and cheap fuels will be diminished and poor management of the transition away from exhaustible resources could potentially increase vulnerability to other less-predictable supply disruptions.

The current distribution of global resources is partly illustrated in Figure 2-7, which shows the major exporters and importers of energy in 2000. Almost every OECD member is a net energy importer, as are a number of rapidly developing Asian countries, such as China, India, Thailand and the Philippines. Depletion of domestic supplies in some countries and regions may lead to an even larger divergence between importers and the major exporters concentrated in North Africa and the Middle East, northern South America and the Former Soviet Union.

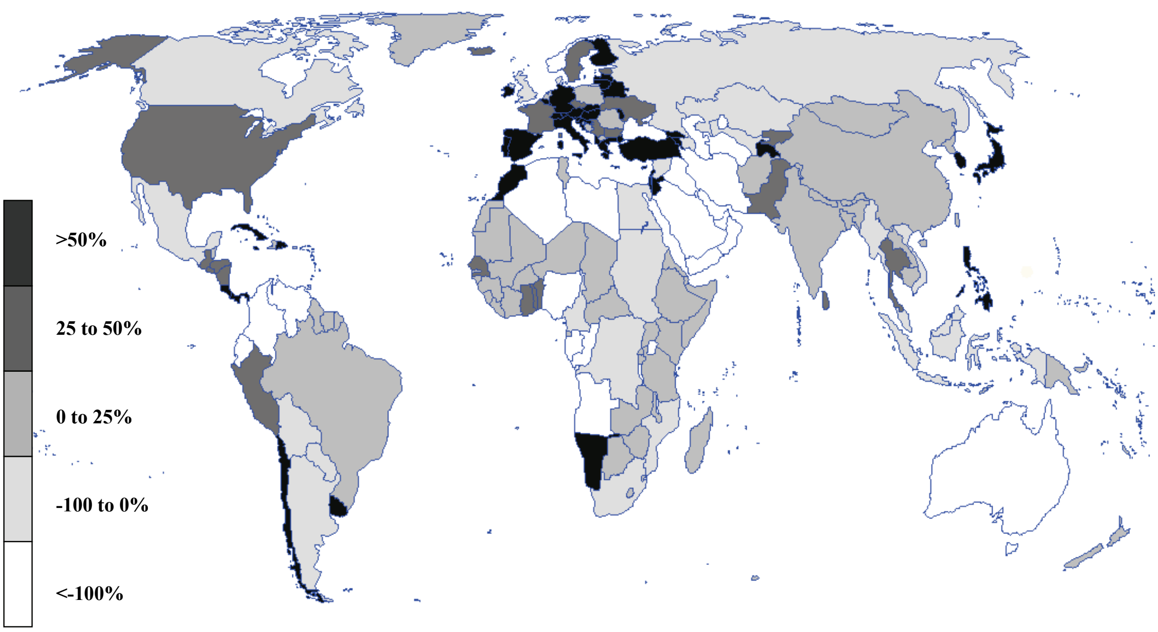

Figure 2-7 Energy imports as a share of commercial energy consumption, 2000
Source: World Bank 2005

Estimates of the distribution of ultimately recoverable fossil fuel resources also give cause to concerns about longer-term energy security. The global geographic distribution of oil resources, including from existing and estimated reserves, enhanced recovery, and unconventional resources, is presented in Figure 2-8 (based on Rogner 1997). Figure 2-8 shows that conventional oil resources are highly unevenly distributed, indicating that maintaining access to secure and affordable energy resources for sustainable development may be a significant challenge in its own right, notwithstanding the potential environmental impacts of fully exploiting global fossil fuel resources.

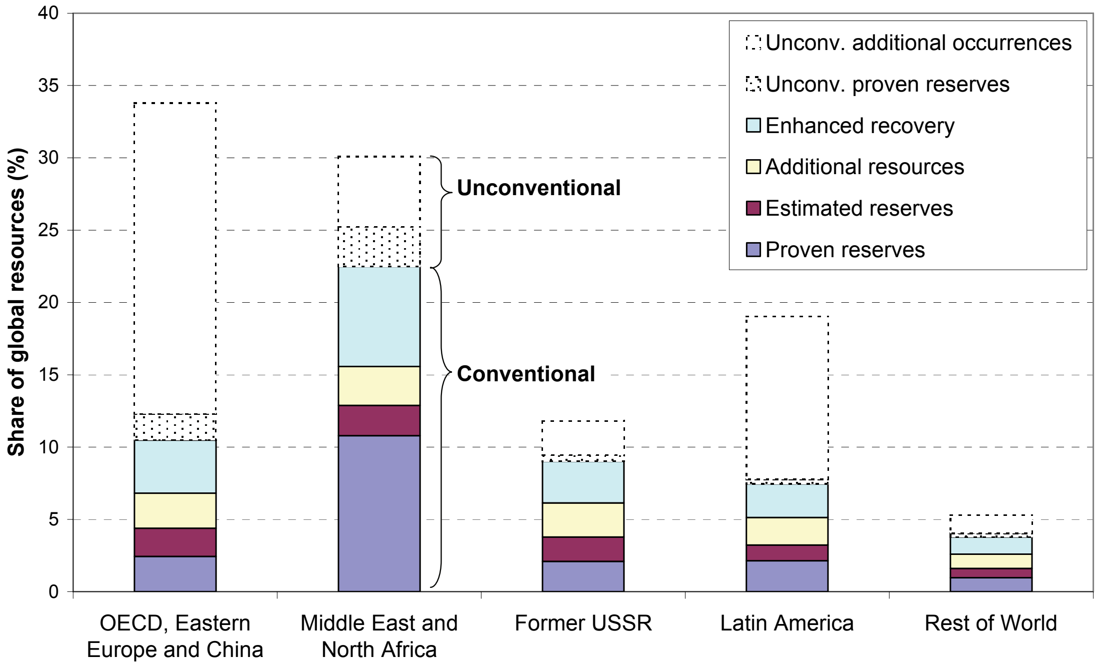

Figure 2-8 Estimated distribution of global oil resources (conventional and unconventional)

Source: Rogner 1997, based on Categories I to VI (thus excluding highly speculative resources)

Climate change and security-of-supply are complex issues, and overcoming the challenges to sustainability posed by either will in all likelihood require the application of a range of technologies and a broad portfolio of policy instruments and support (see Turton and Barreto 2006). This chapter has so far concentrated on some of the major energy issues related to long-term sustainable development, and some of the principle challenges confronting policy-makers. This relates to both of the themes of this dissertation—to develop an integrated policy analysis tool for exploring the challenges confronting policymakers in pursuing sustainable development, and to analyse a scenario of sustainable automobile transport. However, an underlying factor relevant to both of these themes, and critical to any study of sustainable development, is the role of technology. The potential importance of new technologies and technological change in addressing long-term issues of sustainable development warrants a detailed and explicit discussion.

2.2 Technology and sustainable development

Technology and technological change have been critical in economic and social development throughout human history and are likely to continue to play a central role in future human development, including the pursuit of sustainability. Critically, technology can be seen as both a source of threats to sustainable development, and as a potential solution.

The central role of technology in sustainable development can be best appreciated if one considers that technologies of one sort or another have historically influenced each of the key drivers in the IPAT identity presented in Section 2.1.1 (not only the Technology component). The most significant historical affect of technology has perhaps been on income levels (Affluence in IPAT), which increased substantially as a consequence of a massive improvement in labour productivity from the industrial revolution onwards. This productivity improvement occurred only because of the application and diffusion of a range of new technologies, such as steam power, electricity, motorised transport, communication systems, mass-production and automation, to name a few obvious examples (see Grübler 1998 for a more comprehensive review). These technologies revolutionised production, trade, and working conditions and eliminated previous constraints, particularly on the supply of energy or thermodynamic "work" that had restricted economic development (Ayres *et al.* 2003). That is, technologies have facilitated today's high levels of economic throughput that are partly responsible for some of the current threats to sustainable development (Watanabe 1995).

However, as briefly mentioned earlier, technological development also tends to result in a substantial increase in efficiency. For example, historical developments such as the replacement in factories of the steam engine with the electric motor greatly increased energy efficiency, much as the motor car was much more efficient than the horse (Grübler 1998; Ayres *et al.* 2003). However, although energy intensities have declined with economic and technological development (see Figure 2-9), the impact of technology on total output and activity has generally more than offset the impact of efficiency.

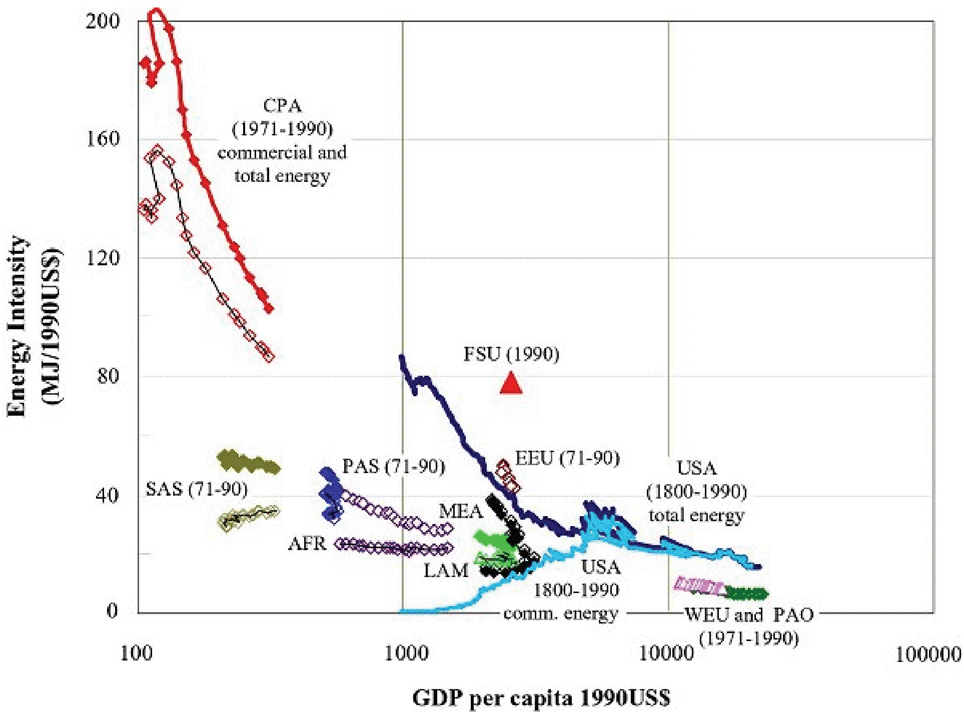

Figure 2-9 Historical improvements in energy intensity accompanying economic growth in different world regions

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

Source: Nakićenović and Swart 2000, Figure 3-13

Nonetheless, technological change has resulted in improved energy efficiency and carbon intensity (see Nakićenović 2002), even at times such improvements weren't necessarily goals in themselves. Accordingly, in addition to threatening sustainable development, technological change appears to have a major potential to contribute to its realisation (Kemp 1997b). This warrants a more detailed analysis of the process of technology development.

2.2.1 Technology development and change

Technology development can be classified into a series of interrelated stages ranging through: invention; innovation; niche market diffusion; large-scale diffusion; eventual saturation; and decline with the emergence of competitors (Schumpeter 1934; Grübler *et al.* 1999). The first stage—*invention*—is the least predictable and is often thought of as involving basic research, individual inventors and unexpected breakthroughs. Most potential technologies never progress past this stage, and there can also often be a substantial break in time before a practical application of an invention is realised. This application—the *innovation* process—appears to benefit from a diversity of actors (or entrepreneurs), each with different expectations about future markets and risks, and employing alternative strategies. Once the application of a technology is successful in the innovation process, the *first commercialisation* is typically in niche markets where the technology has particularly advantages. This first deployment provides extremely useful opportunities for technology learning, which is discussed in more detail below. Technology learning may be particularly important for the deployment of energy and transport technologies that are more compatible with sustainable development, many of which are currently more expensive than incumbents.

Technology learning

Learning arises from experience and effort with a new technology. In its most basic sense, the more often a specific technology component is manufactured, the more manufacturers learn about making the component, including: how to improve the design; use fewer (or cheaper) inputs; make it in less time; include additional features; and perhaps increase the scale of production (Arrow 1962).

The greatest impact from learning often arises early in a technology's design, with the most rapid reductions in technology cost typically arising from research and development (R&D). However, there are also important learning impacts in large-scale production. These include the combination of simple economies of scale from upscaling production sizes, learning how to optimise repetitive production steps, and employing mass production techniques (Grübler 1998). Nonetheless, the benefits of learning diminish as more and more experience is gained.

Since the focus of this dissertation is on energy sustainability, it is important to stress that technology learning has historically affected the cost of a range of alternative energy technologies. Figure 2-10 illustrates how the costs of three electricity generation technologies—gas turbines; wind turbines; and solar photovoltaic (PV) cells—have decreased substantially with increasing experience, illustrated in the figure in terms of cumulative installations of each technology. Figure 2-10 also shows, as mentioned above, that the rate of learning may be more rapid during the technology design phase. However, in addition Figure 2-10 shows that within each development phase the rate at which the costs of a particular technology decline with learning is roughly linear on a double-logarithmic plot, indicating an exponential relationship whereby each doubling of experience leads to a roughly constant percentage reduction in costs. The rate at which costs decline with each doubling of experience (called the "learning rate") has been calculated for a range of energy technologies in a number of studies, and McDonald and Schrattenholzer (2001) present a fairly comprehensive overview, with estimated learning rates ranging from -11 to +35 percent for different technologies. The highest rates were observed for technologies such as PV and early development stages of some other technologies, such as gas turbines. The apparent negative learning case was more to do with poor market competition, although it should also be mentioned that the opposite of technology learning—forgetting—is also possible if critical learning-by-doing know-how is lost (see Grübler 1998).

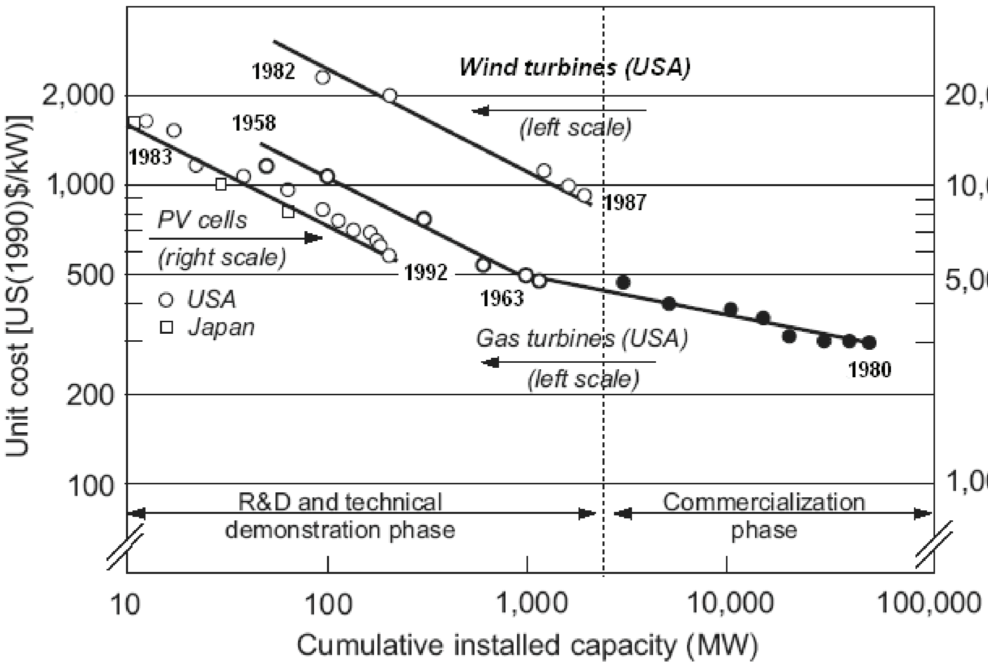

Figure 2-10 Historical impact of technology learning on unit costs of gas and wind turbines, and solar photovoltaic (PV) cells

Source: IIASA-WEC 1995, Figure 4-7

Accordingly, technology learning has already been an important mechanism of energy system development, and goes a long way towards explaining historical changes in the fuel and technology mix (Nakićenović 2002; Grübler *et al.* 1999). Since many of the threats to sustainable development emerging from today's energy system have arisen primarily because of the current dependence on one set of fuels and technologies (i.e., fossil fuels), then future technology learning and its impact on alternative technologies may be critical for overcoming these threats in the long term.

Returning to the stages in the technology lifecycle, the learning arising from the first commercialisation of a technology, including both "learning-by-doing" and "learning-by-using", can lead to cost reductions and performance improvements that enable the technology to be applied more widely, eventually leading to pervasive *diffusion*. During this phase of development, much of the learning opportunities arise from standardisation and mass-production. Technologies typically diffuse outward in space and time from a centre of innovation (Grübler 1998). However, the rate of diffusion may be more rapid in new markets because the technology is typically substantially improved through learning-by-doing during the earlier deployment in the innovation centre, although diffusion is also affected by the suitability of a technology, and the conditions outside the centre of innovation may be quite different, leading to a lower level of final adoption.

The ultimate level of adoption, the success of diffusion, and the life of a technology may also depend on complementary technologies and systems—or technology clusters—and the emergence of competitors.

Technology clusters

Technologies are often thought of as individual items, such as the automobile or, more specifically, the internal combustion engine (ICE). However, technologies need to be considered within the context of complementary and reinforcing systems, technologies and institutions. The "best" technology depends critically on other social and technological influences, which themselves are influenced by the dominant technology paradigm (or cluster). For example, the dominance of the ICE is reinforced by the large and mature petroleum refining industry, fuel distribution system, and road network, and even by the organisation of human settlements and industry in many parts of the world. Accordingly, the introduction of a new technology to replace the ICE, such as the fuel cell (which is discussed in more detail in the following chapters), requires not only the development of a superior engine technology (and the retooling of automobile manufacturing), but also a new fuel production, processing and distribution system. Moreover, this is only a small change that does not fundamentally challenge the automobile paradigm; a more radical shift to an alternative to the automobile would require changes to a much larger set of systems.

The main implication of the existence of reinforcing technology clusters is that an existing combination of technologies and systems can help sustain the dominance of, and "lock in", particular technologies, even if competitors emerge (Grübler 1998). This is critical when considering the features of sustainable development explored in this dissertation, including the emergence of a sustainable global automobile transport system. Moreover, it highlights one of the features of the policy analysis framework outlined in the following chapter—an adequate representation of the full network of technologies that are either competing or complementary within the energy system.

Technology clusters become perhaps increasingly important in sustaining particular technologies during later stages of development, as technologies reach *maturity*, and improvement potentials from learning diminish. Despite the impact of reinforcing clusters, superior competitors may eventually come to dominate, and the market share of the incumbent technology slowly *declines*, perhaps first to niche markets before eventually becoming insignificant.

Importantly, the description of technological development above is highly stylised, and unpredictable jumps and breaks can occur, with new applications being found for existing technologies, thereby creating new markets and potentially allowing a technology to "tunnel through" to a new cluster (Grübler *et al.* 1999).

Given the potential importance of technological change in sustainable development, the following chapter in this dissertation focuses specifically on including detailed representation of features of technology dynamics in a policy analysis tool for analysing sustainable development. This is particularly important for addressing the second theme of this dissertation, which relates to exploring the possible emergence of a sustainable transport system, in which new technologies and fuels are likely to play an important role. However, it is useful to examine first how the transport sector is currently threatening sustainable development, and hence the motivation for our focus on sustainable mobility.

2.3 Transport and energy sustainability

The global transport sector today is a major consumer of energy, accounting for around 28 percent of global final-energy consumption in 2000. This equates to over 80 EJ, almost 96 percent of which is petroleum products such as motor gasoline, diesel oil, jet kerosene and so on, with the remainder supplied by gas, biofuels (mainly ethanol), electricity and a small amount of coal (see Figure 2-11). The almost total dependence of transport on petroleum fuels already creates challenges to sustainable development in terms of maintaining access to secure supplies of energy, and greenhouse gas abatement.

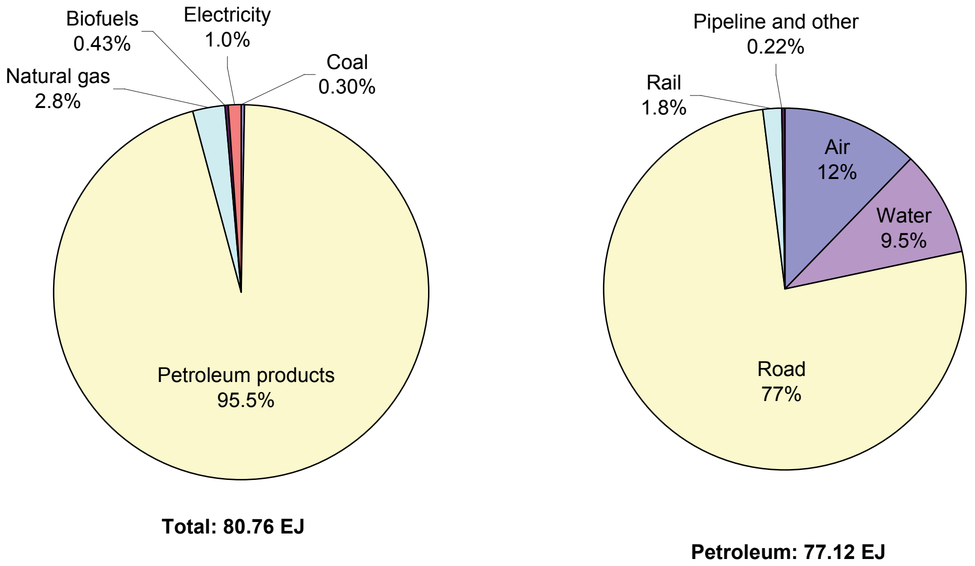

Figure 2-11 Mix of fuels used in global transportation, and consumption of petroleum by different transport modes, 2000

Source: IEA 2003a; IEA 2003b

In addition to the sector's dependence on petroleum products, transportation also accounts for a majority (60 percent) of all the petroleum used by end-use sectors,[3] and road vehicles accounted for 77 percent of this in 2000. Figure 2-11 shows that the remaining 23 percent is divided mainly between air transport (12 percent), mostly jet kerosene, and water-based transport (10 percent), primarily heavy diesel oil. Within the road transport subsector, private automobiles are a major energy consumer. In developed countries it is estimated that private automobiles were responsible for around two-thirds of total road transport energy use in 2000 (based on Landwehr and Marie-Lilliu 2002; FHA 1996; Davis and Diegel 2004; IRF 2000; EIA 1999). The current share is smaller in today's developing world regions, but experience in industrialised countries implies that there is significant future growth potential, and that private automobile travel represents one of the major challenges to sustainable development from transport (see Appendix A for a snapshot of current automobile ownership levels).

Looking at historical trends, transport energy consumption has grown strongly over the past 30 years, in line with global economic growth (IEA 2003a; IEA 2003b), as illustrated in Figure 2-12. Most of the growth, however, is concentrated in the road and air transport

[3] Note, this includes also fuels used for international air and water transport.

sectors, where energy demand more than doubled between the early 1970s and 2000. Private automobile travel demand during the same period is estimated to have increased to over 2.5 times the level in the early 1970s.

Despite the fact that average private vehicle energy efficiencies have improved over the historical period in Figure 2-12, this has been largely offset by increasing demands for travel and decreasing vehicle occupancy rates (Davis and Diegel 2004), so that private vehicle energy use continues to grow strongly. This partly explains the particular attention paid to passenger road vehicle transportation, and the possible emergence of sustainable automobile transport in this dissertation.

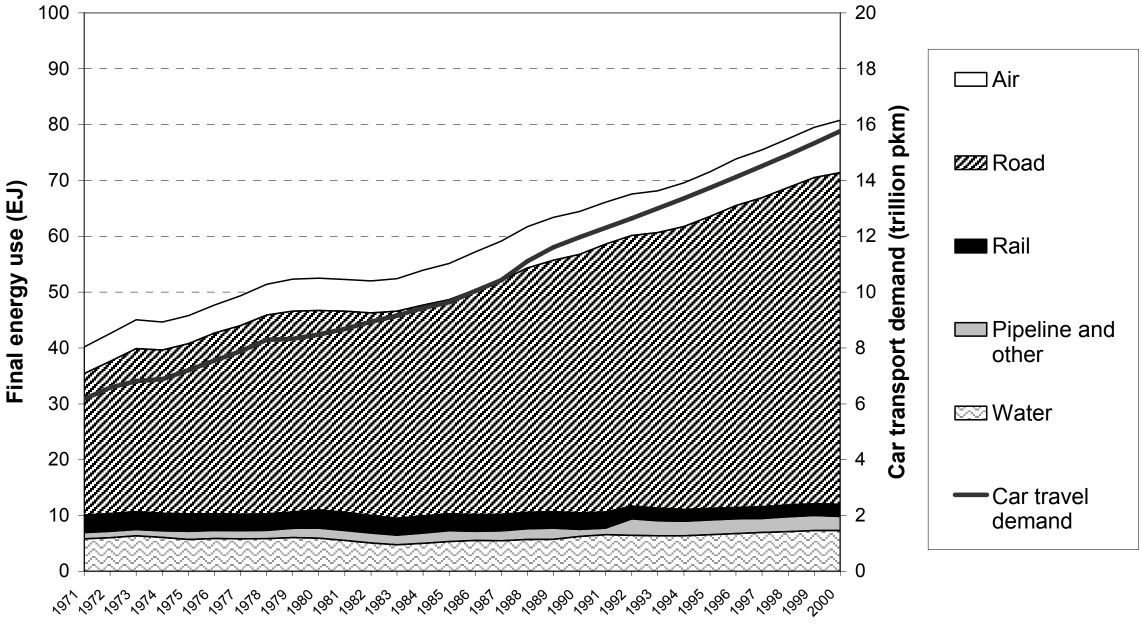

Figure 2-12 Historical energy use in transport and car travel demand, 1971-2000
Source: IEA 2003a; IEA 2003b; Schafer 1995; Schafer 1998; Schafer and Victor 2000

As with total energy use (see Section 2.1) transport energy use, and road transport energy use in particular appear to correlate very closely with economic activity, as shown in Figure 2-13. One potential implication of this relationship is that the economic development needed to improve welfare and overcome poverty in today's developing countries looks likely to coincide with increased road transport demand and energy use. A number of nearer-term projections suggest that global transport energy demand could increase to 120-135 EJ by 2020 (EIA 2002; IEA 2004), with the lower estimate consistent with consumption of 145 EJ by 2030 (IEA 2004), compared to around 80 EJ in 2000. In passenger transport, without either a substantial reduction in demand for mobility or a shift towards public transportation (mass transit), both of which run counter to current global trends, curtailing this growth in energy demand is a significant challenge. In fact, based on historical experience, transport is one of the sectors presenting some of the greatest challenges to achieving environmental and social sustainability. One of the questions this dissertation attempts to explore is whether the level of personal mobility in developed regions, and achieving the mobility aspirations of the developing world, can be compatible with sustainable development.

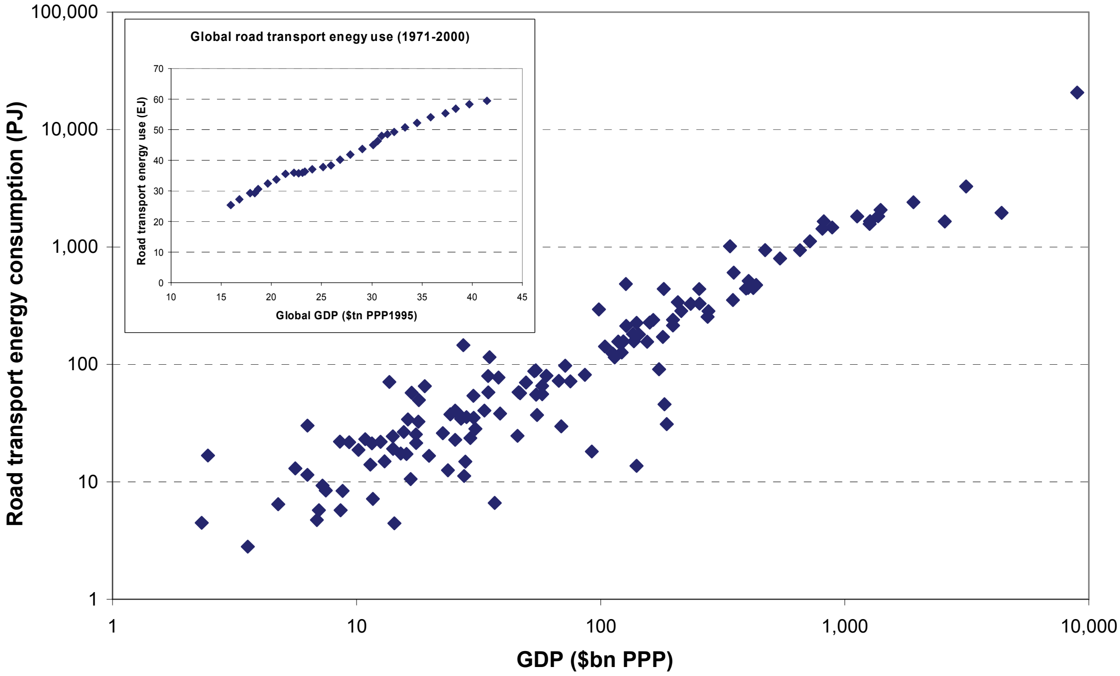

Figure 2-13 Relationship between road transport energy consumption and economic output, 2000

Source: IEA 2003a; IEA 2003b; IEA 2003c; IEA 2003d

To illustrate the relative contribution of transport to one of the challenges to sustainability—climate change—in the recent past, Figure 2-14 shows global emissions of CO_2 from fuel combustion from different broad activities. Figure 2-14 shows that the direct emissions from manufacturing, services and the residential sector have been roughly steady for 30 years, and most of the growth is apparently from electricity generation. This reflects the fact that the end-use sectors have shifted away from direct fuel combustion to greater use of electricity, because it is a flexible, convenient and clean fuel for the end user.[4] The other source of emissions that is growing rapidly is transport, and in the last 30 years this sector accounted for almost all of the growth in energy emissions outside the electricity sector. Increasing emissions from road transport have driven much of this growth, and this mode accounted for close to 18 percent of global CO_2 emissions from fossil fuel combustion in 2000, up from around 12 percent in the early 1970s. Figure 2-14 shows that total annual CO_2 emissions from road transport increased from roughly 475 million tonnes of carbon (Mt C) in 1971 to almost 1,130 Mt C in 2000. A continuation of these trends in emissions implies that transport, in particular road transport and private automobile use, may account for an increasingly large share of global greenhouse gas emissions in the future. As alluded to, this represents a potential challenge to long-term sustainable development, and reinforces the notion that transport is likely to be an increasingly important target for mitigation policy intervention and technology deployment.

[4] Electricity's share of final-energy consumption increased from 10 to almost 16 percent between 1971 and 2000.

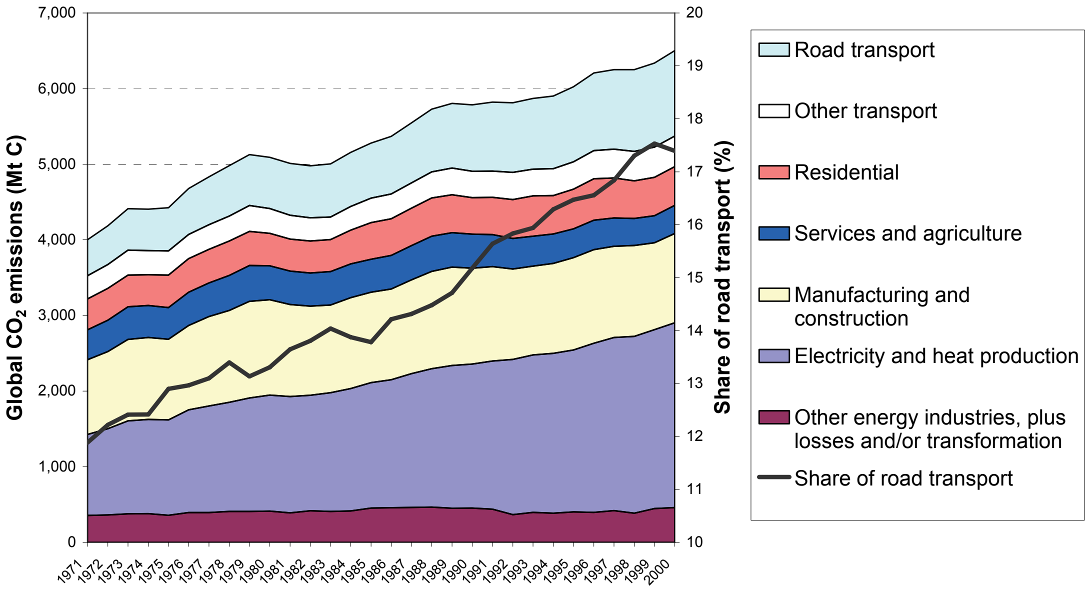

Figure 2-14 Global carbon emissions from fossil fuel combustion, 1971-2000

Source: IEA 2003a; IEA 2003b; IEA 2003c; IEA 2003d

Looking on a broad geographical basis, in the last thirty years over half of the growth in global road transport emissions occurred in OECD countries, and emissions originating from this region represent an important existing threat to sustainable development. However, emissions from road transport have been growing much faster in many developing regions, as illustrated in Table 2-1, which shows that growth in non-OECD Asia outpaced that in the rest of the world, although even after three decades of rapid growth this region was still responsible for only 13.8 percent of global emissions from road transport in 2000. These growth trends have important implications for medium- to long-term greenhouse gas emission abatement and imply, as mentioned, that the biggest future threats from transport to the goals of sustainable development may emerge in today's developing regions. Accordingly, realising a sustainable transport system is a major challenge confronting policy makers throughout the world.

Table 2-1 Road transport CO_2 emissions, regional shares and growth rates

	Annual growth in emissions			Share of emissions				Share of global population
	1971-1980 (%)	1980-1990 (%)	1990-2000 (%)	1971 (%)	1980 (%)	1990 (%)	2000 (%)	2000 (%)
OECD	*2.9*	*2.0*	*2.1*	78.9	71.7	67.3	64.6	15.3
Economies in transition[a]	*5.8*	*2.8*	*-2.4*	7.5	8.8	8.9	5.4	6.8
Asia (non-OECD)	*10.4*	*8.0*	*7.1*	3.1	5.4	8.9	13.8	53.5
Africa and Middle East	*10.4*	*3.4*	*3.8*	3.5	6.0	6.5	7.3	16.0
Latin America	*5.9*	*2.8*	*3.3*	6.9	8.1	8.3	8.8	8.5
World total	*4.0*	*2.6*	*2.6*	100.0	100.0	100.0	100.0	100.0

a Central and Eastern Europe, and the former Soviet Union.

Source: IEA 2003a; IEA 2003b; IEA 2003c; IEA 2003d

2.4 Conclusions: studying the role of transport in sustainable development

Realising sustainable energy and transport systems with a low impact on the global climate, that also achieve other long-term development goals while maintaining energy security may require profound and wide-reaching changes. Transforming global social and economic systems, including global energy and transport systems, from their current structure to one that is compatible with the strategic goals of sustainable development is a long-term process likely to involve continual change to a range of interlinked physical, technological and institutional systems. Understanding how this long-term process might unfold may help guide policy responses aimed at achieving the long-term strategic goals of sustainable development.

Accordingly, this dissertation describes the development of a tool able to analyse energy and transport systems, and their implications for sustainability, that may assist policy makers and researchers to analyse the impact on sustainable development of a range of scenarios and specific policy instruments. To address some of the specific issues raised in this chapter, this tool is applied throughout the dissertation to explore issues related to sustainable transport, including the possible emergence of sustainable automobility over the long term.

The first stage in the construction of this tool is described in the following chapter, which presents the development of a detailed energy system modelling framework, and the selection of a suitable scenario of basic economic, demographic, transport and other features that will form the basis for analysis in subsequent chapters.

Chapter 3. Energy-systems ERIS modelling framework: scenario development and model extensions

3.1 Introduction

Addressing the challenge of realising sustainable development is an important task facing a range of decision- and policy-makers at regional, national and international levels (e.g. WEHAB 2002; Parris and Kates 2003). As discussed in Chapter 2, a number of the potential threats to sustainable development over the longer term are emerging in the energy and transport sectors, and hence these areas are progressively becoming a major concern and target for policy intervention (IEA 2001a; Schrattenholzer *et al*. 2004).

Many of the most substantial threats to long-term sustainability may well arise well into the 21st century, most likely as a consequence of further development and industrialisation. Moreover, the transformations needed to realise a sustainable global energy system are likely to be profound, emerging only over a long time horizon as existing energy and transport infrastructure and systems are replaced. Responding to these longer-term issues may be particularly challenging for policy-makers more familiar with pursuing shorter-term objectives.

In order to support the development of effective and efficient policy initiatives aimed at realising sustainability in the energy and transport sectors over the longer term suitable analysis tools are required. This chapter seeks to begin to address these needs from two perspectives. Firstly, given the long-term nature of challenges to, and the possible emergence of, a sustainable world, this chapter describes in detail the selection and construction of a long-term scenario to explore sustainable development. Secondly, this chapter presents the development of the ERIS (Energy Research and Investment Strategies) model, a core sub-module of the policy and scenario analysis tool applied in this dissertation to study sustainable energy and transport system development.

The following section addresses the selection and construction of a scenario suitable for exploring sustainable development, which is then used throughout this dissertation to study different aspects of sustainability and the possible emergence of a global sustainable automobile transport system (although in Chapter 7 some elements of the scenario are updated with more recent information).

3.2 Scenario definition

Understanding how future energy and transport demands may threaten long-term sustainability, or how these systems can be shifted onto a more sustainable path requires an understanding of broader future developments. Given that the future is unknowable, one way to explore possible trajectories for the future of the global energy and transport system is with long-term (to 2100) energy-economy-environment (E3) scenarios. Such scenarios are useful for enhancing our understanding of highly complex systems, such as the development of global energy and transport, which are subject to many interactions and unpredictable or uncertain factors. It should be emphasised, however, that scenarios are not intended to be predictions and only enable us to explore plausible questions of “what if” related to key future uncertainties. They can also illustrate some of the possible impacts of today’s policy and technology decisions, and are therefore an essential tool for policy makers confronting long-term challenges.

It is envisaged that the policy analysis tool developed in this dissertation will be suitable for exploring a range of scenarios. However, to maintain consistency throughout the analyses presented in subsequent chapters, only one underlying scenario is explored in detail, although an extensive range of policy cases is explored. The choice of the specific underlying scenario is guided partly by the second thematic focus of this dissertation (as mentioned in Chapter 1) to investigate the role of transport, particularly the role of the private automobile and personal mobility in sustainable development. However, the main basis of selection is to construct a scenario suited to providing credible nearer-term policy insights for addressing longer-term challenges, despite future uncertainties. Accordingly, the scenario presented here is based on drivers, including economic, institutional and technological, that are consistent with current and historical experience.

Importantly, for this exercise it is not necessary to develop all elements of a scenario from scratch since many scenarios are available already, such as the 40 scenarios presented in the Special Report on Emissions Scenarios (SRES) from the Intergovernmental Panel on Climate Change (Nakićenović and Swart 2000).[5] These scenarios of overall demographic, economic and technological development were used by the Intergovernmental Panel on Climate Change (IPCC) to represent a range of future uncertainties and their impact on GHG emissions (in the absence of climate policies). All of these scenarios were constructed from four main "storylines", and some of the key features of these storylines are presented in Table 3-1.

Table 3-1 Storyline features from the SRES

	Storylines			
	A1	A2	B1	B2
Population (2100)	Low	High	Low	Median
Economic growth	Very high	Median	High	Median
Global income equality	High	Low	High	Median
Technological change	High	Low	Median	Median
Energy demand	High	High	Low	Median

Source: Kram *et al.* 2000

Within the set in Table 3-1 there are several storylines describing future worlds in which basic economic and social drivers are consistent with a number of the principles of sustainable development (including economic and social sustainability), and which may be suitable for exploring the potential emergence of a sustainable energy and transport system. However, we want to avoid using a scenario which relies on heroic or utopian assumptions, since these are less likely to provide useful policy insights, and are inconsistent with current institutions and driving forces. For instance, very rapid economic growth and technological change, or rapid convergence between incomes in the developed and developing worlds, although perhaps

[5] Which also reviewed over 400 global and regional scenarios of greenhouse gas emissions (Nakicenovic and Swart 2000, Section 2).

desirable from a sustainable development perspective, are divergent from much of historical experience and many current trends, which may take a long time to change.

For this reason, as a starting point the B2 storyline from the SRES (Nakićenović and Swart 2000; Riahi and Roehrl 2000) was selected. In Table 3-1 we can see that the B2 storyline describes a world in which demographic, economic and technological drivers are in the centre of the range of all the SRES storylines. B2 also presents a world where there is a strong emphasis on local solutions to economic, social and environmental sustainability, which makes it well-suited for examining sustainable development (Nakićenović and Swart 2000). Below we describe in more detail, and quantify some of the key B2 scenario variables for 11 major world regions, presented in Figure 3-1. Later in this subsection these key drivers are used to develop a scenario of passenger transport, facilitating the investigation in later chapters of the possible development of a sustainable global transport system.

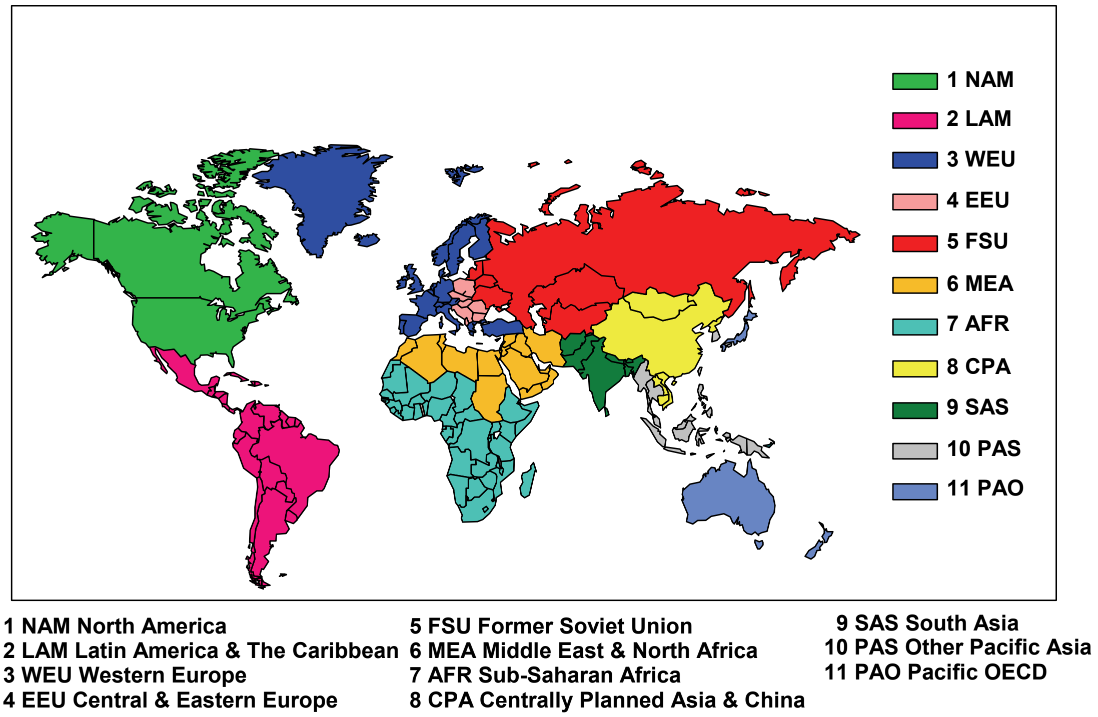

Figure 3-1 World regions used in this analysis

Five regions portray the so-called industrialised regions and the economies in transition (NAM, WEU, PAO, FSU, EEU). Six additional regions represent the developing world (CPA, SAS, PAS), LAM, AFR, MEA).

3.2.1 Basic scenario drivers

The B2 scenario closely follows the median population and economic growth trajectories of a large number of scenario studies (see Nakićenović and Swart 2000, Chapter 2). In other words, the economic and demographic trend assumptions in the B2 scenario are plausible and relatively uncontroversial, and are based on current institutional frameworks. The demographic trends under the B2 scenario are constructed on the basis that "…education and welfare programs are widely pursued, resulting in reductions in mortality and, to a lesser extent, fertility…" leading to a long-term population of 10.4 billion by 2100 (Nakićenović and Swart 2000; UN 1998). Figure 3-2 shows the population in each world region over the period 2000-2100 under this scenario.

The economic trends in the B2 scenario, in addition to following a median growth trajectory, also reflect some of the elements of a sustainable development scenario, based on the criteria described in Box 2-1 of Chapter 2. For example, in the B2 scenario differences in economic growth across world regions are gradually reduced, and high priority is given to human welfare and equality within regions (Nakićenović and Swart 2000). Growth in regional per capita GDPs—expressed on the basis of purchasing-power parities (PPP)—is presented in Figure 3-3, which shows that by the end of the 21st century all but three world regions achieve levels of material prosperity at least equal to the levels prevailing in today's developed regions. Even the more slowly developing regions—Africa, the Middle East and South Asia—undergo substantial improvements in their absolute and relative material well-being. Overall, there is a "considerable improvement in interregional equity" in this development scenario (Nakićenović and Swart 2000), and this is reflected in the world regional Gini index presented in Figure 3-4 (Gini 1921).[6]

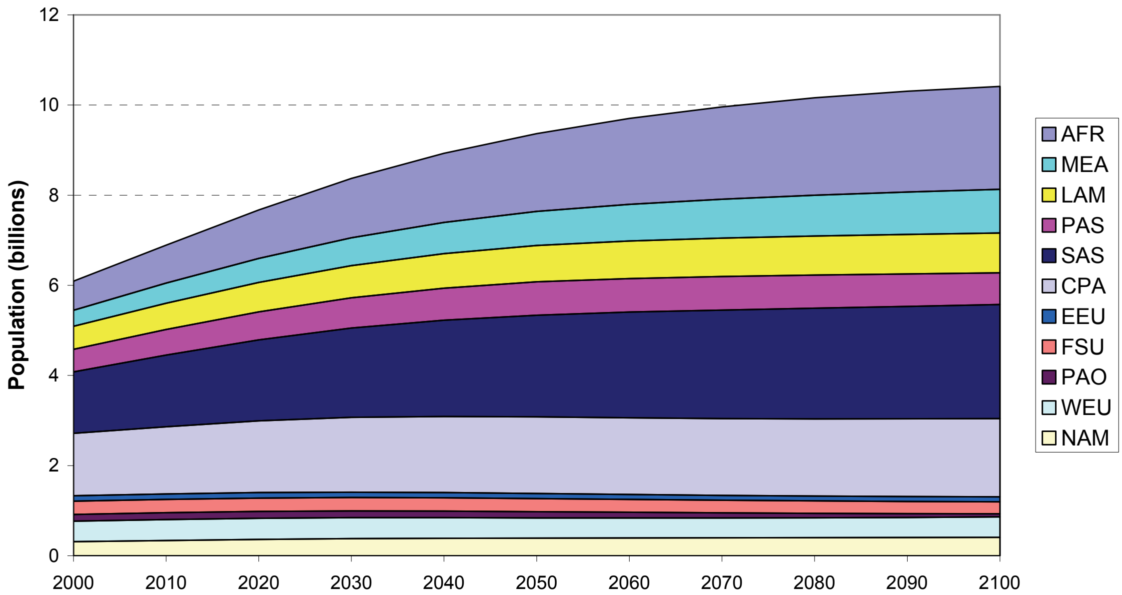

Figure 3-2 Scenario of global population growth

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

[6] The Gini index is generally used to measure the degree of income inequality within a country. For example, a Gini index for household income is calculated by first constructing a Lorenz curve, in which the cumulative share of household income is plotted against the cumulative share of households arranged from poorest to richest. The index is then calculated as one (1) minus twice the area under the Lorenz curve (with the result usually multiplied by 100). Perfect equality results in a Gini of zero, and a perfect inequality in a Gini of 100.

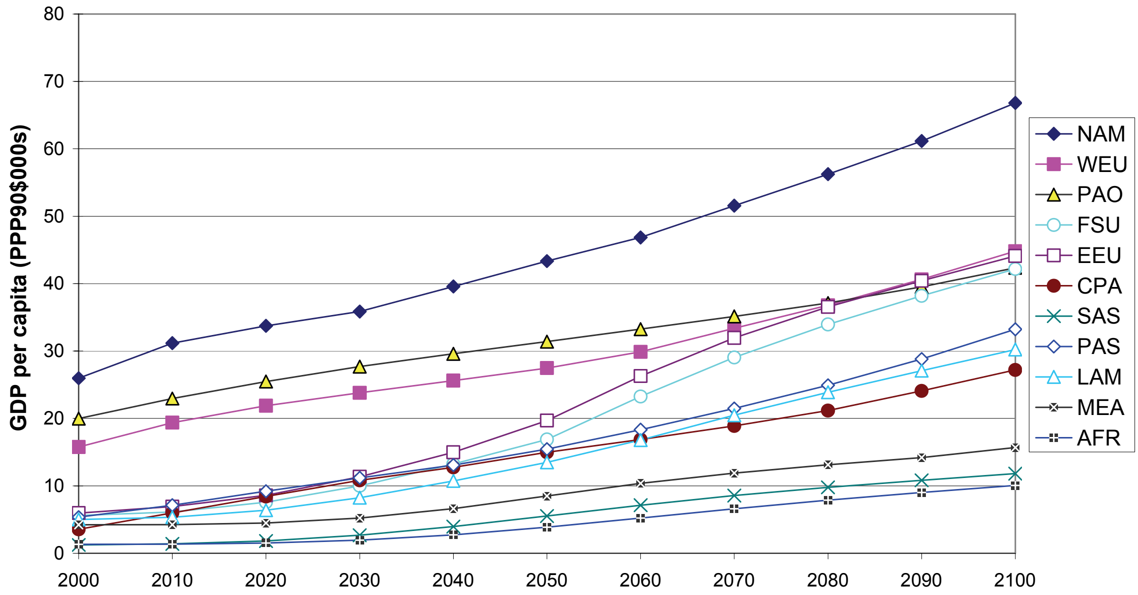

Figure 3-3 Scenario of economic growth

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

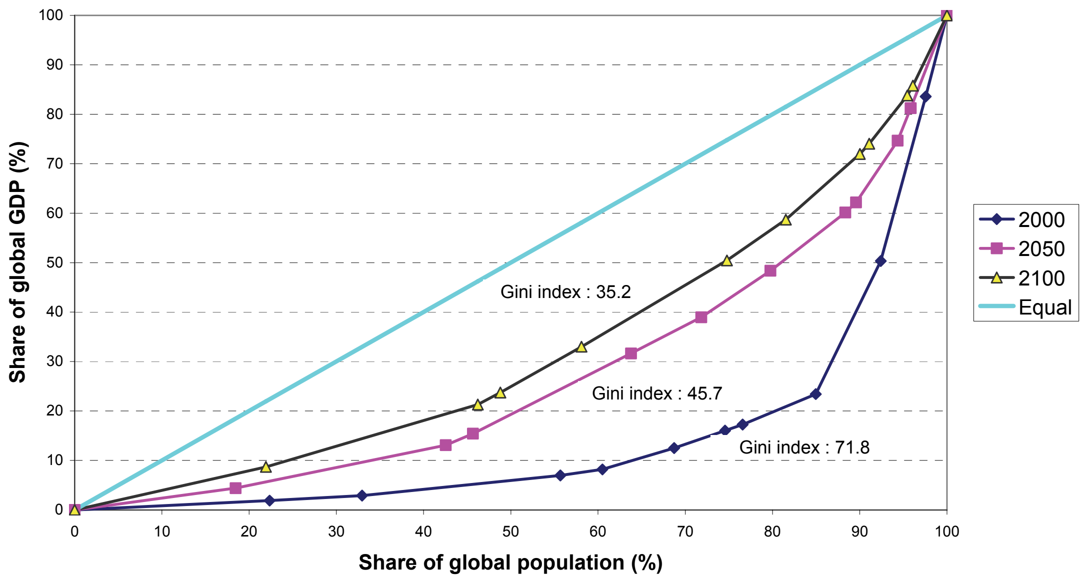

Figure 3-4 Increasing equality between world regions

Importantly, this regional Gini index cannot be interpreted in the same way as a conventional Gini index because it is based on world regional averages and highly aggregated.[7] However, it provides an indication of inequality between regions. Global inequality in 2000 (with a Gini index of 71.8 from Figure 3-4) is worse, for example, than the level of national inequality in Namibia (70.7), Sierra Leone (62.9) and Colombia (57.6) in 2004 (UNDP 2004). By 2050, global inequality is comparable to the 2004 national level of inequality in Russia (45.6) or China (44.7). In 2100, it is around the level today in the United Kingdom (36) or Australia (35.2), but worse than in Sweden (25.0). Importantly, this scenario does not rely on heroic assumptions about a rapid convergence in global per capita incomes, so regional differences in income, and hence inequality, persists at the end of the century. However, the distribution of income in the world in 2100 under this scenario is much more equal than in 2000, and the divergence in incomes in 2100 between different regions is similar to the current divergence among OECD countries.[8]

Technological development and diffusion under the B2 scenario is moderate, and innovations are regionally heterogeneous, with uneven technological change across the globe. On average, energy efficiency under the B2 scenario improves at about one percent per year, the same rate that "has prevailed over the past 100 years in countries for which long-term…data are available." (Nakićenović and Swart 2000, Section 4.4.5.7). The regional improvements in energy intensity—measured in MJ of final energy per dollar of GDP expressed in PPP—are presented in Figure 3-5, and these rates are used in this analysis to define improvements for all activities other than passenger transport, which is discussed below in Section 3.2.2.

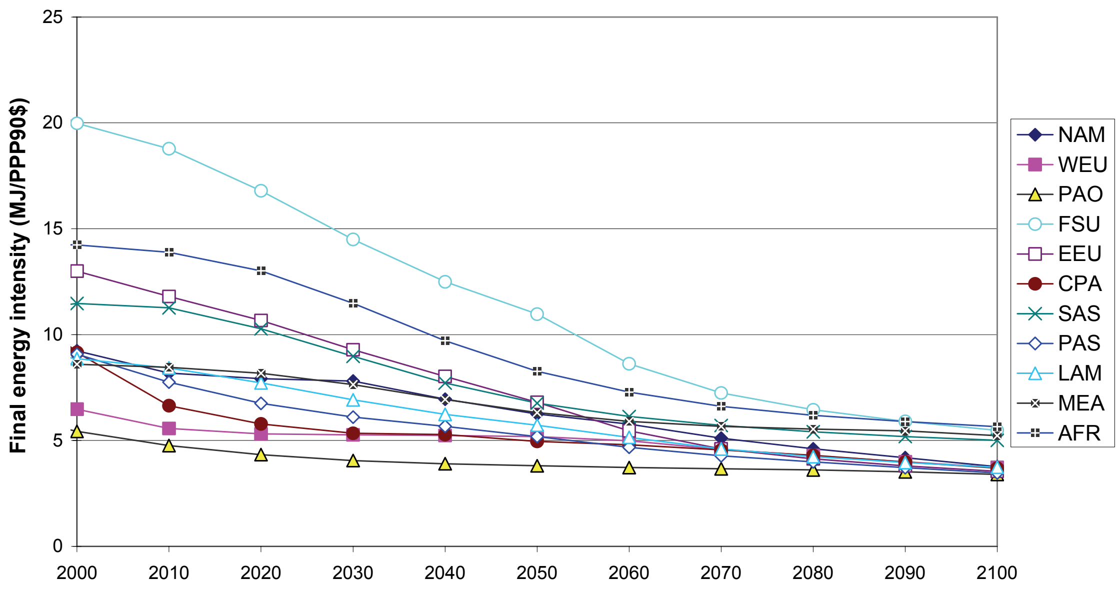

Figure 3-5 Scenario of developments in energy intensity

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

[7] Within each region there is expected to be inequality which will also affect the Gini index, although under this scenario intraregional equality also improves, perhaps more than global equality (Nakicenovic and Swart 2000, Section 4.3.4).

[8] The ratio of GDP per capita (in purchasing power parity terms) between the richest and poorest region declines from close to 18 in 2000 to 6.5 in 2100. For comparison, the ratio between the OECD members Luxembourg and Turkey in 2000 was approximately 9, and between Norway and Turkey around 5.6 (IBRD 2004).

Accordingly, as mentioned, B2 represents a scenario which is consistent with some of the central elements of economic and social sustainability. In other words, this scenario forms a good basis for exploring strategies for sustainable transport. However, it should be underlined that this scenario is only one of many possibilities that are consistent with the particular principles of sustainable development used here (see Box 2-1 in Chapter 2). The B2 scenario is chosen because it is not significantly divergent from historical and prevailing trends, and relies on existing institutions, and is therefore intuitively plausible (and credible) to today's policymakers. However, this does not necessarily mean that this future is more likely than any other scenario. Importantly, by using a scenario based on many current trends and institutions, we can make an assessment of whether these structures are incompatible with a sustainable energy system, and hence whether it may be necessary to break from existing trends.

The basic scenario features described in this chapter can now be used for formulating other scenario elements in a consistent way. These elements include estimates of future energy and transport demand, based on the demographic, economic and other drivers of the B2 scenario.

For example, as a starting point electric and non-electric demands in each world region were taken from the B2 scenario quantified with the MESSAGE model for the IPCC Special Report on Emission Scenarios (Riahi and Roehrl 2000; Nakićenović and Swart 2000),[9] which incorporates the energy intensity improvements illustrated in Figure 3-5. These demands were calibrated to the year 2000 (IEA 2003a; IEA 2003b), and from this starting point global non-electric demand increases by around 80 percent between 2000 and 2100 (to 315 EJ), while electricity demand increases 9-fold to almost 140 PWh, reflecting a shift to cleaner and more convenient energy carriers (Riahi and Roehrl 2000). Specific features of these demands are discussed in much more detail in the analyses in Chapter 4 and Chapter 5, and are recalculated using the methodology described in Chapter 6. Importantly, however, throughout this dissertation it is not necessarily intended to reproduce or emulate the results of the SRES quantification. Moreover, a deliberate decision was made not to seek to reproduce the transport scenario implied within B2.

One reason for adopting an alternative approach to transportation is that this sector is considered in a very aggregated and stylised way in the SRES, which is unsuitable for addressing the second theme of this dissertation focusing on sustainable automobility. However, a more important, and somewhat related, rationale relates to a potential inconsistency within the B2 storyline used in the SRES, where "[u]rban and transport infrastructure is a particular focus of community innovation, contributing to a low level of car dependence and less urban sprawl" (Nakićenović and Swart 2000, Section 4.3.4). Given other elements of the B2 storyline this represents a somewhat courageous assumption. In particular, the gradual changes in demographics, geopolitics, productivity, technology and other "salient scenario characteristics" in the B2 scenario (Nakićenović and Swart 2000, Section 4.4.2.4), do not appear to be consistent with rapid changes in systems with high inertia, such as transport infrastructure and urban form. Moreover, the B2 storyline envisages a continued reliance on current institutional frameworks (Nakićenović and Swart 2000, Section 4.3.4) which have generally shown themselves unable to shift trends in personal mobility towards lower car dependence.[10]

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[9] The only exception is demands in the passenger car sub-sector, for which projections are based on the model of Schafer and Victor (2000) with some adjustments.

[10] In addition, if one simply makes the assumption that there will be low levels of car dependence, than one can solve many of the potential challenges to sustainable development immediately. This provides very few policy insights, and so is not particularly helpful.

Accordingly, a passenger transport demand projection was constructed more in line with a continuation of current trends, and other elements of the B2 scenario, to overcome potential limitations of earlier approaches (which are not confined to the SRES). This projection of personal mobility is used throughout this dissertation and is described in detail in the following section.[11]

3.2.2 Transport scenario

3.2.2.1 Passenger automobile transport scenario

Elements of the B2 scenario were applied to develop a projection of passenger transportation demand to 2100, based on an enhanced version of the passenger transportation demand model of Schafer and Victor (2000). The original model of Schafer and Victor (2000) estimated future vehicle occupancy, travel demand and modal choice to 2050 for the IS92a/e scenario (Leggett *et al.* 1992) on the basis of passenger travel time and money share budgets. Specifically, this model exploits the apparent historical and cross-regional stability of travel budgets, where people on average spend slightly more than one hour per day and 10-15 percent of income on travel (Zahavi and Talvitie 1980; Schafer and Victor 2000). The implication of this stability is that increasing incomes lead to a preference for faster modes of transport.

However, the B2 scenario applied here differs considerably from the IS92a/e scenarios employed by Schafer and Victor (2000), both in terms of population and economic growth, and because of a considerably longer timeframe in B2 (to 2100 rather than 2050). Accordingly, it was necessary to extrapolate and modify some of the model regression equations used by Schafer and Victor (2000), taking into account realistic trends in vehicle ownership, the share of various modes and likely occupancy and utilisation levels.

Nonetheless, the main factors influencing future travel demand and modal choice remain much the same in the projection developed here, with population and GDP growth from B2 largely determining future travel budgets, modal choice and the total volume of transport.[12] We explore the implications of this transport scenario in more detail in Chapter 4 and Chapter 7, but the main feature worth mentioning at this stage is that this scenario does not envisage a major shift to more public transport (mass transit), a redesign of urban areas, or any significant attenuation of demand growth arising from information or communications technology. It can be argued that this development in transport is consistent with other aspects of the B2 storyline presented in Section 3.2.1.

Global passenger car[13] travel demand under this scenario is presented in Figure 3-6, which also presents an estimate of historical demand. In this scenario, global demand grows from

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[11] However, in Chapter 7 this projection is updated with a revised B2 population and economic growth pathway incorporating recent information.

[12] Recall, that the B2 scenario is based on the long-term UN Medium 1998 population projection of 10.4 billion by 2100 (UN 1998), combined with intermediate levels of economic development where world GDP grows to approximately 11-times 1990 levels by 2100 (Nakicenovic and Swart 2000). See Section 3.2.1 for more details.

[13] Private passenger vehicle transport can normally be thought of as car transport. However, in North America a majority of the light vehicles sold today are light-duty trucks instead of cars (with light trucks accounting for 52.8 percent of light vehicle sales in 2003, according to Davis and Diegel (2004, Table 4.9)). Since most of these are used for personal transport (75 percent in 1997, based on Davis and Diegel (2004, Table 5.7)), it is more accurate to use the broader term “private passenger vehicle”. For convenience, however, we will use this term and the term “car” interchangeably to cover private passenger vehicles.

roughly 16 trillion passenger-km in 2000 to 41 trillion pkm in 2050, and 53 trillion pkm in 2100.[14] Clearly, the trajectory of future travel demand shown in Figure 3-6 has major social (in terms of urban planning, mobility, access), economic (infrastructure, congestion) and environmental (emissions, resource extraction) implications. One key question, for instance, is whether this future level of transport demand, propelled by continued economic growth, will necessarily undermine the achievement of the goals of sustainability, thereby necessitating restrictions on personal mobility;[15] or whether technological and structural changes will enable the transport and energy system to develop in ways that are compatible with the principles of sustainable development. Later chapters will explore this in more detail.

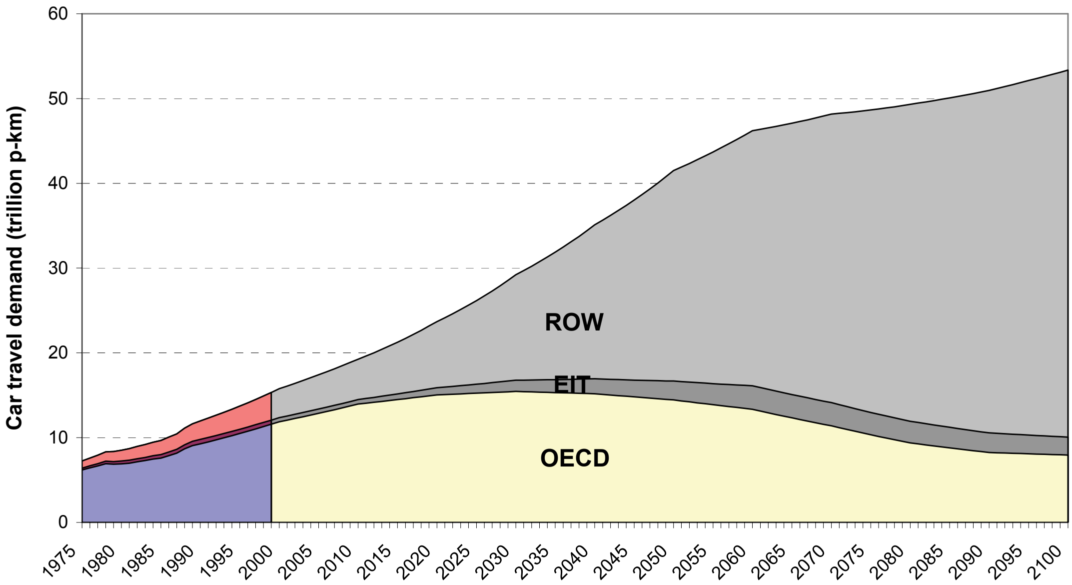

Figure 3-6 Scenario of global passenger car travel demand

Returning to the transport scenario developed here, Figure 3-6 also shows that most of the growth occurs in developing regions (ROW), with total demand in industrialised regions (OECD and economies in transition (EIT)) falling below year 2000 levels before the end of the century under the population trajectory assumed in the B2 scenario. It is also worth noting that in this travel demand scenario, aggregate car transportation in developing regions surpasses that in the industrialised world in around 2040-2050. In subsequent chapters we combine this travel demand scenario with an energy system model to elucidate possible energy supply scenarios, and to explore the implications for sustainable development.

[14] This can be compared to 36-37 trillion pkm of car travel estimated by WBSCD (2004) for 2050, although this study relied on a very different set of assumptions. For example, WBSCD (2004) assumed higher economic growth in some world regions, but a weaker link between income and travel demand in many regions. Schafer and Victor (2000) estimated total car travel demand in 2050 at around 45 trillion pkm, but again this was also based on a different scenario (IS92a, see Leggett *et al.* 1992) which included, among other features, higher growth in developed regions than B2. However, not all scenarios concur closely with the one presented here. For example, Azar *et al.* (2004) project total car travel in 2100 to reach 113 pkm (compared to 53 pkm here), mainly because of an assumption that there is only a limited shift to faster modes, which implies that increasing incomes lead to a declining share of expenditure on transport at higher incomes or a willingness to devote much more time to travel—a trend yet to be observed (Schafer and Victor 2000).

[15] Although restricting access to particular modes of transport could help achieve some aspects of environmental sustainability, it may undermine other aspects of development, including economic activity, social sustainability and human welfare.

The long-term stabilisation and decline of transport demand in industrialised regions is one of the key features of the scenario presented in Figure 3-6, and can be attributed partly to stabilisation and decline of population, but mostly to a shift to faster and more expensive modes of transportation as incomes rise, which itself has significant implications in terms of resource consumption, pollution and infrastructure needs (and these are incorporated in the analysis in subsequent chapters). Over a longer time horizon, the developing regions could also be expected to undergo such a stabilisation and decline. However, under the scenario assumptions used here, this does not occur this century. Another important trend that is assumed to occur in developing countries as a result of increasing incomes is a decline in the relative contribution of two-wheelers (which are not included in Figure 3-6—see Appendix A for a brief discussion of the importance of this transport mode today in some developing countries). Nonetheless, the ownership rates of two-wheelers are assumed in this scenario to increase over the longer term, up to the level in the OECD Pacific—roughly 0.1 per person—which is the highest of all world regions (WBCSD 2004). Despite this increase, in this scenario increasing automobile travel means that two-wheelers play only a minor role in satisfying aggregate future transport demand, except in a few niche markets.

To better understand the implications of this scenario for vehicle travel and energy demand, the passenger transport demand projection in Figure 3-6 (in passenger-km) was converted into a scenario of demand for passenger vehicle travel (in km), based on the scenario of future vehicle occupancies shown in Figure 3-7 (Schafer and Victor 2000; Turton and Barreto 2004; Turton and Barreto 2005).

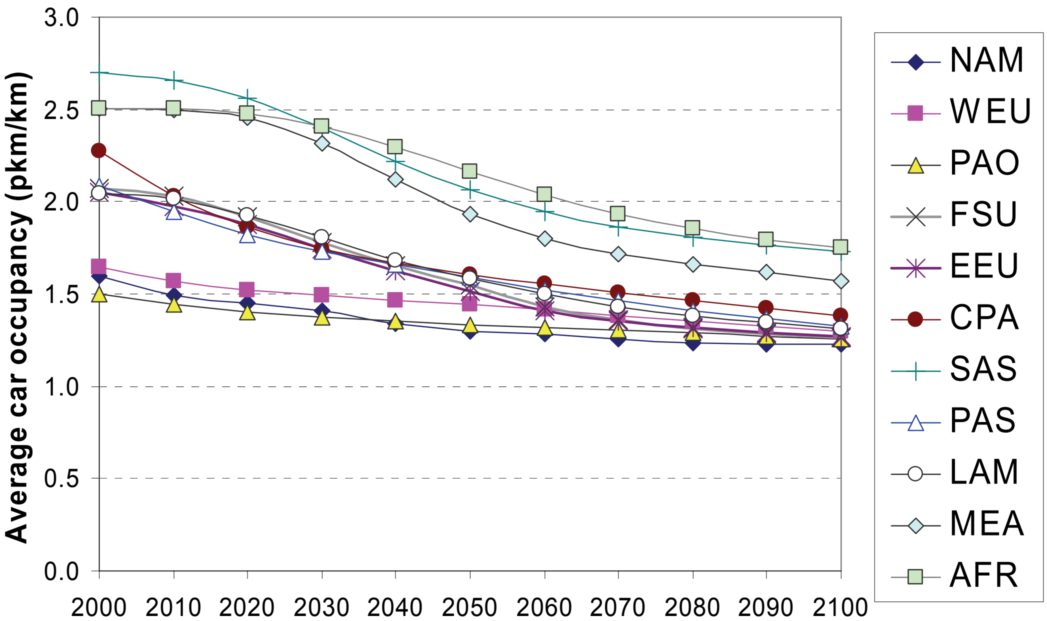

Figure 3-7 Scenario of future average car occupancy rates

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

In developed regions, average vehicle (car) occupancy rates have been declining (EEA 2002; Davis and Diegel 2004) and this trend is expected to continue with further increases in incomes, although the average occupancy is not expected to decline much below 1.25 people per vehicle. In developing regions, developments in vehicle occupancy are expected to follow roughly the historical path of developed regions.[16] When combined with the passenger travel demand scenario presented above, these occupancies imply the passenger car travel demand scenario presented in Figure 3-8, where car transportation grows from roughly 9 trillion kilometres of travel in 2000 to around 37 trillion kilometres in 2100.

On a regional level, a number of specific features of the scenario presented in Figure 3-8 are worth noting. For instance, in industrialised regions demand peaks and then declines in the second half of the 21st century (for the reasons discussed above in the description of Figure 3-6), while in reforming countries of central and eastern Europe and the former Soviet Union demand increases across most of the century, although these regions continue to account for only a small fraction of global demand. In contrast, demand growth is very vigorous in developing regions and by the end of the 21st century they dominate the demand for passenger car travel at the global level.

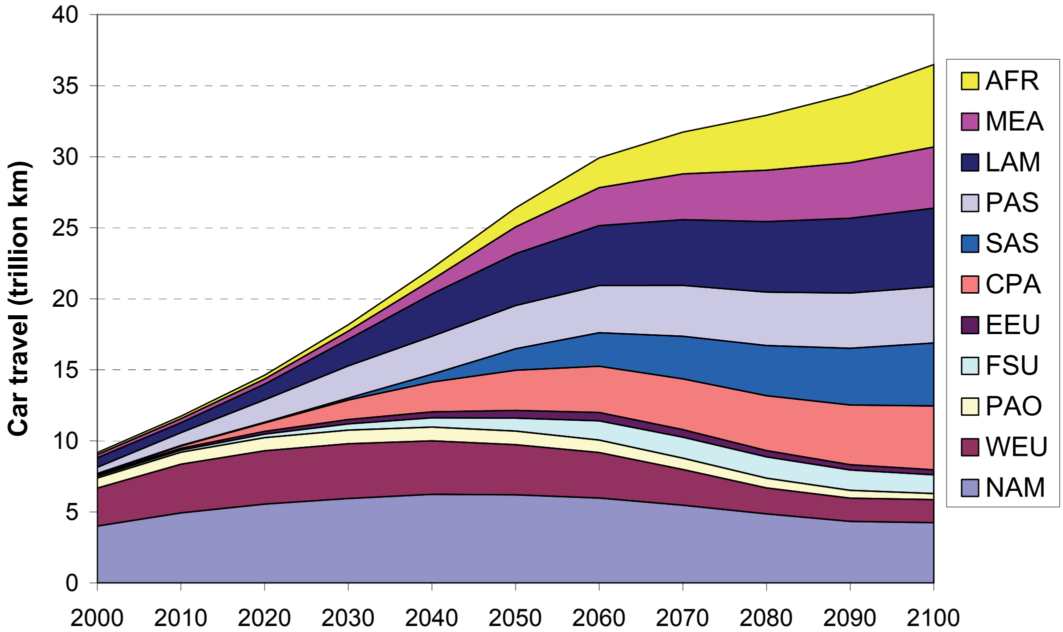

Figure 3-8 Scenario of future global car travel

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

The overall increase in car travel illustrated in Figure 3-8 represents one of the principal challenges to sustainable development arising in the transport sector. It is worth restating that this is the level of vehicle use that is consistent with the population and economic development described in the B2 scenario (see Section 3.2.1), which itself is needed to realise other aspects of sustainable development, including poverty alleviation and greater global

[16] Occupancies in 2000 were estimated using EEA (2002), Davis and Diegel (2004) and Michaelis *et al.* (1996).

equality.[17] Moreover, the assumptions described above, upon which this travel scenario are based, are consistent with the current institutional framework, gradual changes in economic and social factors, and the repeat of many of the historical trends experienced by today's developed countries in the developing world. The implications of this demand growth for the global passenger vehicle market are briefly discussed below.

3.2.2.2 Vehicle numbers and ownership

To explore the potential implications of the vehicle travel scenario presented above in Figure 3-8 in terms of global vehicle ownership, and as a reality check on the overall scenario, vehicle numbers were estimated based on utilisation rates (or annual vehicle driving distances). Estimates of 1990-2000 vehicle utilisation rates were derived from data on vehicle numbers (AAMA 1996; AAMA 1997; FHA 1996; Davis and Diegel 2004; IRF 2000; EIA 1999) and Schafer and Victor's (2000) models of occupancy and travel demand. These trends were extrapolated based on convergence around 10-16,000 km per vehicle *per annum* (Schafer 1995; Schafer 1998) for all world regions except North America, where average vehicle travel distances are assumed to converge to around 22,000 km *per annum*. The choice of these values is based on historical trends and analysis done by Schafer (1995).

It must be stressed, however, that estimating future average vehicle driving distances is highly uncertain. Economic development, on the one hand, results in higher incomes and improved road transport infrastructure, which may encourage a shift to private transportation and longer average vehicle driving distances. On the other hand, economic development also results in improvements in public transportation infrastructure, higher car ownership (if one household owns more than one car, for example, average travel per vehicle may decrease), and higher levels of congestion. Looking at estimates for 1990-2000 it is difficult to find a clear pattern across different regions between average driving distance and economic development alone. Developing regions may exhibit high average driving distances, and this is the case for Latin America (LAM) and the Middle East (MEA), but North America also exhibits high average driving distances. In addition to the factors mention above we can speculate that geophysical characteristics, urban form, population density and cultural factors may also be highly influential (for example, see Turton 2006b). Accordingly, the average vehicle driving distance estimates applied here are uncertain, and are heavily influenced by trends in today's developed regions.

Figure 3-9 presents the implied levels of vehicle ownership in the scenario developed here based on the estimated vehicle driving distances described above. Figure 3-9 shows three main trends: a) car ownership in developed regions peaks and begins to decline as higher incomes (and higher travel money budget) make faster modes more attractive; b) a catching-up of Eastern Europe (EEU) and the Former Soviet Union (FSU); and c) rapid growth in some developing regions—notably Other Pacific Asia (PAS) and Latin America (LAM). By 2050 in this scenario, global average vehicle ownership is projected to double compared to 2000. Between 2050 and 2100, however private automobile ownership rates are expected to increase by only roughly 25 percent, largely because the large increase in today's developing regions is partly offset by a decline ownership levels in developed regions and regions in transition. It should be mentioned that this scenario anticipates that an initially rapid growth in ownership in many of today's developing regions (for example, in centrally planned Asia (CPA)) will give way to a slower and steady increase, with car ownership peaking at a lower level than in developed countries (Grübler 1998). This occurs partly because patterns of settlement in these

[17] Although it is obviously not the only possible path for achieving these goals.

regions have evolved under different influences, and higher population densities and congestion levels (from high vehicle density) are felt at an earlier stage of development than occurred in today's industrialised countries (see Turton 2006b for a more detailed analysis of the forces affecting vehicle numbers in the CPA region).

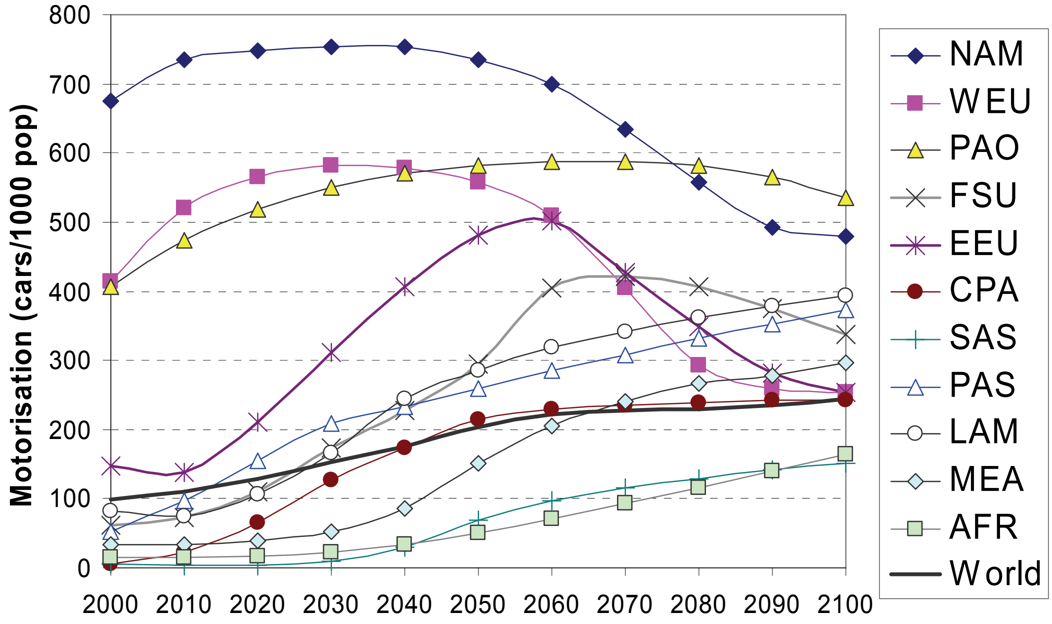

Figure 3-9 Future passenger vehicle ownership rates

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

3.2.2.3 Vehicle efficiencies

The previous section has illustrated potential future challenges to sustainable development emerging in the automobile transport sector over the 21st century. However, the future choice of vehicle technologies may be one critical element for overcoming these challenges and achieving a gradual transformation to a sustainable world. Alternative vehicle drivetrain technologies[18]—discussed in Appendix B1—with improved efficiency such as fuel cells (FCs) and hybrid electric systems may represent a means by which to reduce greenhouse gas emissions and other pollutants, and maintain energy security, although there remains significant uncertainty and debate on the timing of these technology options (see e.g. Keith and Farrell 2003; Azar *et al.* 2003). The potential role of new drivetrain technologies in realising a sustainable transport system over the longer-term is a key focus of this dissertation, and is explored in more detail in Chapter 4 and Chapter 7. Further, the efficiencies of specific alternative vehicle drivetrain technologies are an important input for the policy analysis tool developed here, and are discussed in more detail in Section 3.3.3.4 below.

[18] The term 'drivetrain' refers to the motive power system covering on-board fuel processing, engine, transmission, system control and any power regeneration, such as with hybrid electric vehicles (HEVs).

However, within the context of defining the overall scenario that will form the basis of subsequent analyses, it is also important to consider possible vehicle efficiency improvements aside from those associated with alternative drivetrains. Based on a number of sources, a moderately conservative assessment is that fuel consumption rates could be reduced by 50 percent over the 21st century through a combination of improved aerodynamics, lighter materials, reduced rolling resistance tyres and other improvements (NAS 2002; Weiss *et al*. 2000; NRC 1992; OTA 1995; IEA 1997; Schafer *et al.* 1999; Lightfoot and Green 2001). However, one driving force from the B2 scenario outlined above likely to offset the full realisation of this potential is increasing incomes (which are themselves one important aspect of the sustainable development). As evidenced in today's industrialised countries, income growth will in all likelihood continue to shift consumer preferences towards larger vehicles and vehicles with more energy-consuming onboard systems.[19] Potential efficiency improvements and trends towards larger vehicles are discussed in more detail in Appendix B2.

Based on these two offsetting factors—technical improvements *versus* vehicle size—the average efficiency of conventional vehicles (that is, those employing the petroleum-fueled internal combustion engine) is assumed to improve at 2 percent per decade in the overall scenario explored here. This rate of improvement implies that roughly 55 percent of the technical improvement achievable without switching drivetrains (50 percent, as mentioned above) is offset by a shift to larger vehicles, or vehicles with more energy-consuming features.

3.2.2.4 Other transport

A projection of future global demand in other sectors, comprising air, water, rail, pipeline and freight road transportation was also derived from the B2 scenario. In the case of air transportation, the modified passenger transport demand model discussed above in Section 3.2.2.1 (based on the work of Schafer and Victor (2000)) was used to develop estimates consistent with trends in private motor vehicle (PMV) travel. This passenger-kilometre demand for air travel was then converted to an energy demand according to air transport energy efficiency estimates, that were assumed to converge towards 0.9 MJ/pkm by 2100—around a 50 percent improvement in the estimated level of the current most efficient region (PAO) (IEA 2003a; IEA 2003b; Schafer and Victor 2000)—resulting from stock turnover, improvements in aircraft design and higher capacity utilisation. Air transport demand is discussed in more detail in Chapter 6 and Chapter 7.

Energy demand growth rates for other transport sectors, mainly freight, were taken directly from the growth rates for total transport demand from the B2 scenario quantification with the MESSAGE model and applied to 2000 baseline data (IEA 2003a; IEA 2003b) to generate a projection scenario, implicitly incorporating efficiency improvements assumed in the B2 scenario (Riahi and Roehrl 2000). Accordingly, both air and freight transport activity are not modelled in as much detail as automobile transport demand, and the freight transport energy demand scenario employed here is very similar to that in SRES B2.

To recapitulate, so far this section has outlined demographic, economic and other scenario features, and how these translate into a scenario of passenger car and other transport demand consistent with the SRES B2 storyline. One additional key scenario driver highly relevant to

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[19] This trend is seen in both the USA and Europe, and in both cases average passenger vehicle fuel economies have improved relatively little, if at all, since 1985 (Davis and Diegel 2004; ECMT 2003; IEA 2003e).

the energy system relates to a physical constraint—the availability of fossil and other fuel resources.

3.2.3 Energy resources

Clearly, the extent and geographical distribution of the primary fuel resource base are among the main uncertainties in assessing long-term energy issues, including security of supply, climate change and the availability of energy for development. The fossil-fuel resource base assumed in this analysis is based on estimates of Rogner (1997). Rogner's (1997) categorisation distinguishes between conventional and unconventional reserves and resources accounting for increasing degrees of geological uncertainty and decreasing degrees of economic attractiveness, although over the long term technological change may substantially alter the picture by improving the ability to identify, quantify and access resources (Rogner 1997, 2000). Here we use Rogner's (1997) estimates for total conventional resources and enhanced recovery, but assume that only around 2,500 billion barrels of unconventional oil, and around 16.6 ZJ of unconventional gas is available, and at 3-4 times the extraction cost of today's conventional fuels.[20] However, Rogner's highly speculative and uncertain estimates of "additional occurrences" of unconventional fuels are excluded.

To illustrate the resource assumptions applied here, the global oil and natural gas resource base is presented in Table 3-2, using Rogner's (1997) notation. Categories I to III represent conventional reserves and resources. Category IV represents the potential for enhanced recovery of conventional resources. Category V corresponds to the identified reserves of unconventional recoverable oil and gas, and Category VI corresponds to unconventional oil and gas resource estimates. The resource categories used in the scenario described here are shaded in Table 3-2 indicating, for instance, that the total oil resource assumed corresponds to roughly 5,500 billion barrels in 2000, which is in line with the more realistic estimates from many other sources (see review by Odell 2004, pp. 45-52).

This resource estimates may appear large particularly compared to recent estimates of proved reserves of around 1,150 billion barrels (BP 2004). However, such lower estimates represent commercial reserves of conventional oil based on current market and technical conditions. In contrast, the estimates of Rogner (1997) attempt to represent the ultimately recoverable resource, comprising existing conventional reserves, estimated additional conventional resources, enhanced recovery from existing oil fields (using advanced recovery technologies), identified unconventional oil reserves (such as shale oils and tar sands), and estimated unconventional resources. More details about the resource base are presented in the third analysis in this dissertation (Chapter 5, see especially Figure 5-1 and Figure 5-2), which deals directly with issues associated with long-term security of energy supply.

Turning to other energy resources, coal supplies are also based on estimates from Rogner (1997) and are considered globally abundant, although they can be limited in some regions. Following Rogner (1997), categories A to E for both hard coal and brown coal have been considered, as shown in Table 3-2. Category A represents proved recoverable reserves. Category B represents additional recoverable resources. Category C represents additional identified reserves while Categories D and E group together additional resources.

[20] It should be noted that this is another point of divergence with the B2 scenario (Riahi and Roehrl 2000, Table 1), which was more optimistic about the size of already identified reserves of unconventional oil that could be recovered "at prevailing market conditions" (1,200 billion barrels), but less confident about further unconventional resources (estimated at only 250 billion barrels).

Table 3-2 Categories of conventional and unconventional oil, gas and coal reserves, resources and additional occurrences, in zetajoules (10^{21} J)

	Conventional reserves and resources	Unconventional reserves and resources			Unconventional and additional occurrences	
Category	I, II, III	IV	V	VI	VII-VIII	Total
Oil	12.4	5.8	1.9	14.1	60	94
Gas	16.5	2.3	5.8	10.8	802	837
	Proved recoverable reserves	Additional recoverable resources	Additional identified reserves	Additional resources		
Category	A	B	C	D	E	Total
Coal	18.7	12.4	23.3	41.4	166	262

Note: The resource categories used in ERIS are shaded.

Most other primary energy resources (such as renewables and fuels for nuclear reactors, accounting for reprocessing) are assumed to be abundant over the time horizon of interest. However, hydroelectric and biomass resources are an exception. Accordingly, the ERIS model also incorporates resource availability estimates of these primary energy sources. In the case of biomass, resource estimates from Rogner (2000) and Fischer and Schrattenholzer (2000), who identified a global potential in 2050 of between 250 and 400 EJ after accounting for land requirements for food and fibre, are used. These estimates are based on the assumption additional 1.3 billion hectares of land globally could be used for biomass production, mostly in the developing world, particularly in Latin America and Africa. In the scenario constructed here, it is assumed that it is not possible to exploit these resources rapidly, and that only 125 EJ of biomass is available in 2020, rising to 235 EJ in 2050 and 320 EJ by 2100.

Together, these estimates of demographic, social, economic and resource constraints constitute the core elements of the scenario used in much of this dissertation in developing the integrated policy analysis tool, and for exploring issues associated with sustainable automobile transport. Other important inputs, such as energy demands were taken from the B2 scenario quantified with the MESSAGE model for the IPCC Special Report on Emission Scenarios (Riahi and Roehrl 2000; Nakićenović and Swart 2000),[21] which incorporates the energy intensity improvements illustrated in Figure 3-5.

Having defined the overall scenario to be used throughout much of this dissertation, including elements encompassing economic development and partial convergence between industrialised and developing countries, regional resource estimates, and future passenger transport demand, this chapter now turns to the construction and expansion of the ERIS model. As briefly mentioned, this model forms a key part of the integrated policy analysis tool developed here.

[21] The only exception is demands in the passenger car sub-sector, for which projections are based on the model of Schafer and Victor (2000) with some adjustments.

3.3 The ERIS energy model

The original ERIS model was developed as a joint effort between the Environmentally Compatible Energy Strategies Program at the International Institute for Applied Systems Analysis (IIASA-ECS) and the Paul Scherrer Institute (PSI) in Switzerland during the European Commission-sponsored TEEM[22] and SAPIENT[23] projects, where it was mainly used to examine issues related to the endogenisation of mechanisms of technological change (Messner 1998; Kypreos *et al*. 2000; Barreto and Kypreos 2000, 2004a, see also Barreto and Klaassen 2004). Accordingly, the ERIS model already includes features such as technology learning (learning-by-doing and learning-by-searching), and detailed "bottom-up" representation of the electricity generation sector and technologies, making it a good starting point for developing a detailed and comprehensive analysis tool for exploring issues related to long-term energy sustainability.

Technically, ERIS is formulated in the GAMS (General Algebraic Modeling System) software for mathematical programming problems. Conceptually, the model can be represented as a system of simultaneous equations, including both equalities, and partial inequalities (≤,≥), representing engineering constraints and energy balances. The ERIS model is 'run' by solving the system of linear equations while maximising or minimising a single variable—for example, total discounted energy system cost. A single solution of the model then encapsulates the details of the energy system, including activity and deployment of different energy technologies, fuel choice, trade and so on.

This section describes the extensions to and recalibration of the ERIS model to make it suitable for studying broader aspects of sustainable development, particularly those related to climate change, security of energy supply and transportation. The extensions represent an important series of steps in the development of the integrated policy assessment framework described in this dissertation. The main modifications to the ERIS model include improvements to the representation of technology detail, comprising:

- development of cluster approach to technological learning;
- disaggregation and additional technological detail in the non-electric sector, particularly automobile transportation; and
- addition of an energy carrier production sector, specifically for hydrogen, alcohol and Fischer-Tropsch liquids production.

Furthermore, a number of features were included to better represent non-energy greenhouse gas emissions, including:

- incorporation of methane and nitrous oxide emissions and abatement cost curves;
- estimates of sulfur dioxide emissions; and
- geological and terrestrial carbon storage.

The addition of these features facilitates the linkage of the ERIS model to the MAGICC climate model (Wigley 2003; Wigley and Raper 1997; Hulme *et al.* 2000), enabling direct estimation of the energy system and other sources of GHGs on climate change—a key element in sustainable development.

[22] Energy Technology Dynamics and Advanced Energy System Modeling
[23] Systems Analysis for Progress and Innovation in Energy Technologies

3.3.1 Spatial detail and time horizon

The first major modification to the ERIS model to make it suitable for exploring sustainable development (as outlined in Chapter 2), was to extend and disaggregate the global coverage to a level of eleven world regions, following the regional structure outlined in Section 3.2.1 above (Messner and Strubegger 1995). As a consequence of this regional disaggregation, and for the purpose of subsequent analysis of security of energy supply (see Chapter 5), it was also necessary to include scope for interregional trade of energy carriers (coal, oil, natural gas and hydrogen) and greenhouse gas (GHG) emission allowances (or permits).

In addition, the model timeframe was selected to be sufficiently long to explore the implications of economic catch-up by developing countries, and long-term climate change and energy security threats. Accordingly, the ERIS model covers the time horizon from 2000 to 2100 with 10-year time steps and, unless specified otherwise, a 5 percent discount rate is applied for all energy cost calculations.

3.3.2 Energy system detail

In earlier versions, the ERIS model consisted of an electric and a non-electric sector. In the electric sector, electricity generation technologies competed to supply an exogenously given electricity demand. In the non-electric sector, aggregate fuel production technologies would compete to supply an exogenously given non-electric demand, corresponding to the aggregation of the demand for final-energy fuels other than electricity.

To construct the current version of the model, this non-electric sector was disaggregated into several sub-sectors, including more detailed fuel production technologies, low-quality and low-temperature heat (district and water heating), stationary high-quality and high-temperature thermal needs and transportation, in order to provide a better representation of the final-energy consumption and increase the technology detail in the model. The transportation sector was further disaggregated with emphasis on the passenger car sub-sector. All these modifications are described in more detail below.

The reference energy system for this new version of the ERIS model is presented in Figure 3-10. The figure shows primary fuels, conversion sectors and final demand sectors. Boxes represent primary fuels, groups of technologies and demand sectors. Figure 3-10 also shows the connections linking fuels with technologies and demand activities, and distinguishes flows of fuels used for secondary energy production (plain lines) and for final demand (dashed lines). To simplify the diagram, vertical parallel bars are used to group together multiple fuels or energy carriers used by one group of technologies.

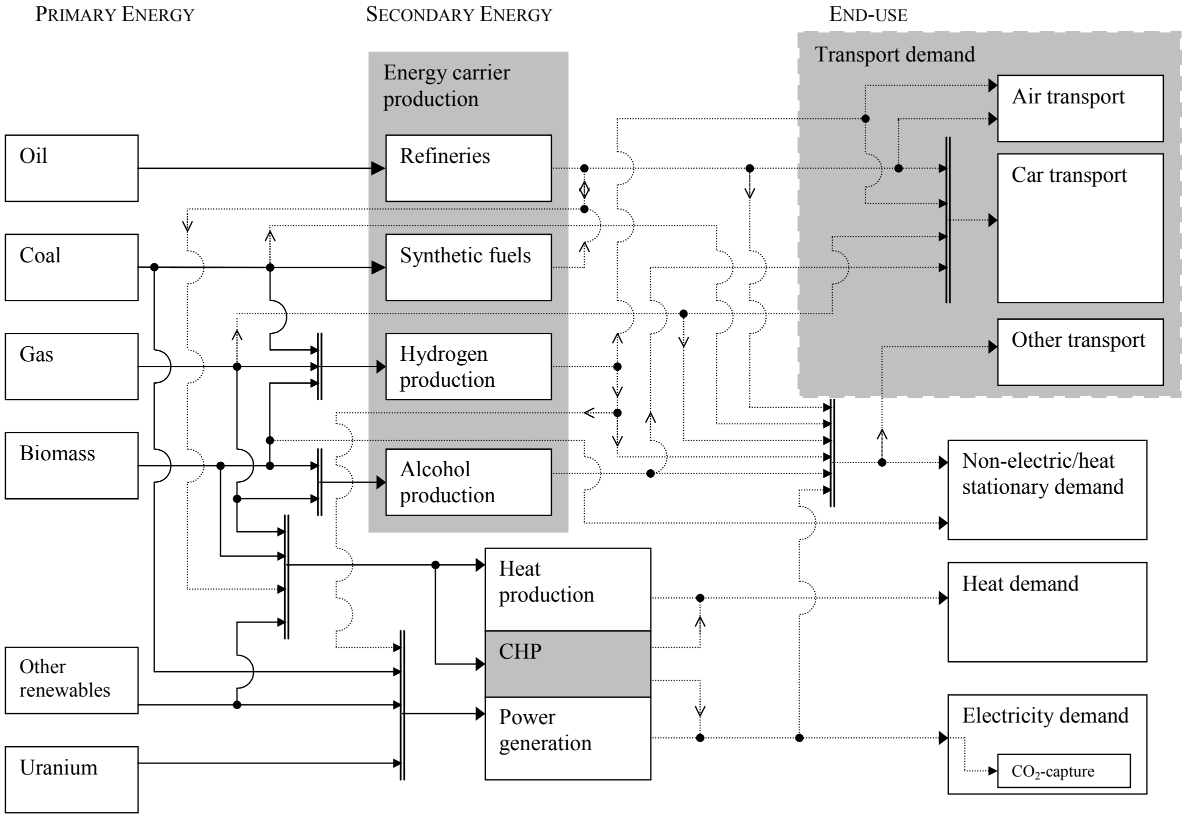

Figure 3-10 ERIS reference energy system

The figure shows primary fuels, conversion sectors and final demand sectors. Boxes represent primary fuels, groups of technologies and demand sectors. The connections linking fuels with technologies and demand activities are shown and flows of fuels used for secondary energy production (plain lines) and for final demand (dashed lines) are distinguished. Vertical parallel bars are used to group together multiple fuels or energy carriers used by one group of technologies.

3.3.3 Disaggregation of end-use sectors

The number of end-use technologies in ERIS was increased to better reflect the characteristics of final-energy demand. Specifically, demand for non-electric energy was disaggregated into demand for low quality heat (district and water heating), stationary high-quality thermal needs, transportation and non-energy uses. New supply-demand balances were added to the model for each of these sectors.

In earlier versions of ERIS, to avoid unrealistic outcomes—such as district heating technologies supplying all the thermal needs of the industrial sector—arbitrary and somewhat unrealistic limits were placed on the shares of demand that each non-electric end-use technology could supply. The updated version of the model developed as part of the realisation of this dissertation ensures that end-use technologies supplying a lower quality energy service (i.e., less convenient, flexible, lower thermodynamic quality), cannot supply higher quality needs. However, ERIS still enables higher-quality fuels (such as electricity) to provide an energy service that could be met by a lower quality fuel. The end-use technologies and the corresponding sectors are discussed briefly below.

3.3.3.1 District heating

The ERIS model allows demand for district heating to be supplied by heat from: cogeneration; direct combustion of coal, oil, gas and biomass; solar thermal production and other renewables (particularly geothermal energy). As mentioned above, demand for heat can be supplied also with higher quality energy sources.

3.3.3.2 Stationary energy

Demand for high quality stationary energy can be supplied from direct combustion of coal, oil, gas, biomass, hydrogen and alcohols, and from electricity. One element of the B2 scenario described in Section 3.2.1 (and many other long-term scenarios) is that electricity becomes an increasingly important energy carrier given that it is a convenient, flexible and clean fuel for the end user, and allowing electricity to supply thermal needs is consistent with this development. So, for example, the ERIS model includes technologies representing the on-site use of hydrogen in fuel cells to generate electricity for thermal needs, in addition to technologies for the combustion of hydrogen for direct thermal use.

3.3.3.3 Non-energy uses

ERIS did not previously account for non-energy uses because it was developed to investigate energy technologies. However, to facilitate the modelling of the threat of climate change to sustainable development, the model must account for GHG emissions and abatement options associated with coal, oil and gas production. Accordingly, all fuel consumption activities are included into the model, thereby ensuring the associated fuel production, and concomitant GHG emissions are included. Estimates of non-energy demand for fuels are an exogenous input to the model, based on the scenario described in Section 3.2.1.

3.3.3.4 Transport

Transportation is a growing concern for the policy makers, both in terms of energy consumption and polluting emissions, and represents a significant potential threat to long-term sustainable development. The main objectives of this dissertation intersect at the nexus of developing and applying analytical tools to understanding the conditions under which a sustainable transport system might evolve, and possible policy and technology actions. Accordingly, the transport sector, in particular passenger car transport, is one of the areas where efforts on ERIS have been concentrated.

The transportation sector in the ERIS has been disaggregated into three main non-electric[24] sub-sectors—passenger motor vehicles (PMVs, cars), air transportation and all other transportation (primarily freight). For the first two sub-sectors, a relatively detailed technology representation is possible. In the aggregate remaining sector, generic technologies are set up to mimic the final-energy consumption. In total, the model distinguishes seventeen technology-fuel combinations across the following categories:

- Surface transport:
    - Combustion technologies
        - coal (mainly locomotive trains with steam engines),
        - petroleum products (for both heavy road, rail and sea transport and light vehicle transport)

[24] Electric rail transportation is treated separately within electric demand

    - natural gas (heavy and light vehicles);
    - alcohol fuels (heavy and light vehicles);
    - hydrogen (heavy and light vehicles);
  - Fuel cell technologies:
    - hydrogen (heavy and light vehicles);
    - alcohol (light vehicles); and
    - petroleum products (light vehicles).
- Air transport:
  - petroleum combustion technologies (mainly jet and propeller engines);
  - hydrogen combustion technologies (although assumed not to be available before 2050, see Airbus 2003);

Hybrid ICE-electric technology variants are also included for a number of passenger car vehicle technologies (a subset of light duty vehicles) listed above (with all FCVs assumed to incorporate hybrid technology). The technologies and sub-sectors are discussed below.

i) Passenger cars

In the case of the passenger car sub-sector, end-use demands are input to the model in terms of kilometres of travel using a scenario such as that presented in Figure 3-8 in Section 3.2.2.1, rather than energy units. This ensures that engine technologies compete on the basis of the energy service; otherwise more efficient technologies would be disadvantaged. In the case of the scenario presented in Section 3.2.2, the demands for km of travel were developed on the basis of the B2 storyline (from which the other final energy demands input to ERIS have also been derived) and a modified version of the passenger transportation demand model of Schafer and Victor (2000).

The suite of end-use technologies that can meet these demands comprise three different engine technologies (the conventional internal combustion engine (ICE), the ICE-electric hybrid, and the fuel cell-battery hybrid) using four different fuels, as shown in Table 3-3. Overall, ERIS models ten technology-fuel combinations for the private automobile. Estimates of the “drivetrain” efficiencies (referring to overall efficiency of fuel processing, engine, transmission, system control and power regeneration) and costs of each of these combinations were derived from Weiss *et al.* (2000; 2003), Thomas *et al.* (2000), Ogden *et al.* (2004) and ADL (2000), and the relative efficiencies are presented in Figure 3-11 (more detail on costs is presented in Appendix B3). For most technologies, the efficiency values represent approximate median values from the sources listed above, with the exception of the alcohol and petroleum fuel cell technologies where the distribution of literature efficiency estimates was bimodal, and we selected the more optimistic median value. Figure 3-11 also presents abbreviated mnemonics for each technology used for convenience later in this chapter (e.g. ICC, IGH, AFC).

Table 3-3 Passenger car technologies and fuels in ERIS

Fuels	Engine technologies		
	Conventional ICE	Hybrid ICE-electric	Fuel cell-battery hybrid
Petroleum products	X	X	X
Natural gas	X	X	
Alcohols	X	X	X
Hydrogen		X	X

Note: three different engine technologies (the conventional internal combustion engine (ICE), the ICE-electric hybrid, and the fuel cell-battery hybrid) are considered using four different fuels (oil products, natural gas, alcohols and hydrogen).

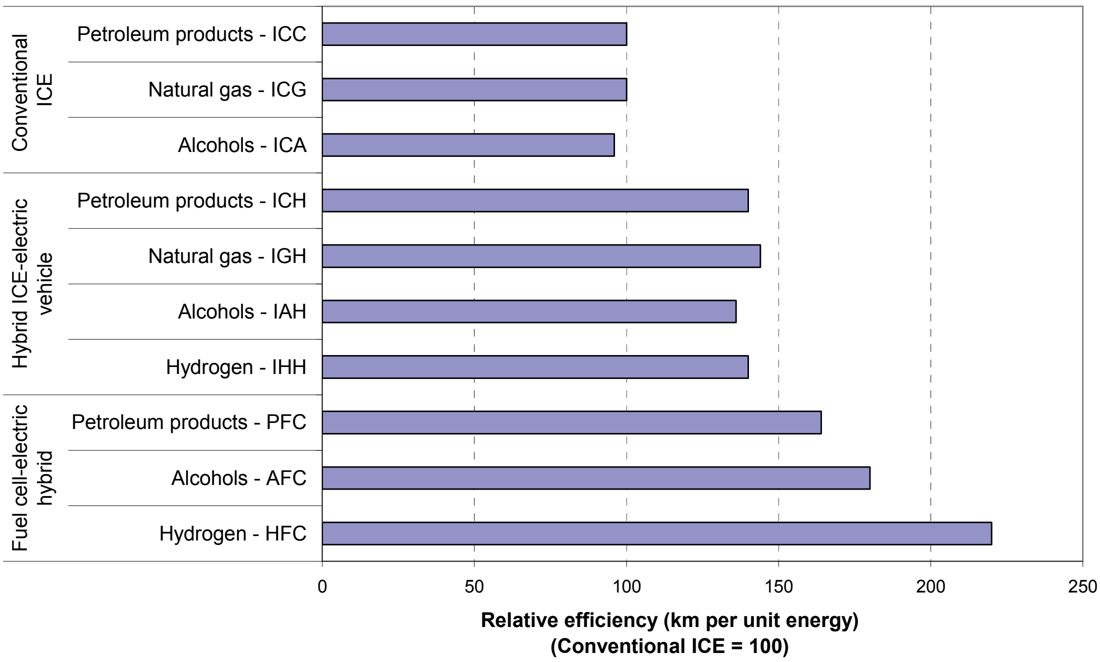

Figure 3-11 Relative drivetrain efficiencies of car technology-fuel combinations

ii) Air transportation

The ERIS model uses a stylised representation of non-car transportation sectors, including air transportation. In this sector it is assumed that only petroleum-based fuels and hydrogen can be used to power aircraft, although hydrogen-fueled aircraft are assumed to be available only from 2050, and that even after this date market penetration is expected to be slow because of various technical and market-acceptance issues (see Airbus 2003). It should be recognised that there may be some scope to increase the technological detail in this sector for analyses specifically interested in air transportation.

For reference, it is worth mentioning that the demand projections for energy used in air transportation from the scenario discussed in Section 3.2 (developed using the B2 scenario and a modified version of the transportation model of Schafer and Victor (2000)) are based on an assumption that aircraft efficiency improves moderately and converges across different world regions (see Section 3.2.2.4).

iii) Other transportation

Freight vehicles (including road, sea and rail) are not modelled in the same level of detail as the passenger transport sector, and are covered by five technologies. The efficiencies of these technologies are influenced by a number of factors. Firstly, the higher utilisation rates of freight vehicles (particularly heavy vehicles) mean that the adoption of new technologies is generally assumed to be faster. On the other hand, the driving cycle of heavy vehicles (with less stop-start driving and acceleration) means that they benefit less from hybridization (e.g., hybrid ICE-battery systems). Looking at the application of fuel cell technologies to freight vehicles, the main drawbacks of using hydrogen FCs—related to fuel storage volume and distribution infrastructure—are less significant for large vehicles that often refuel at a small number of dedicated stations. Given other advantages of hydrogen FC technology, it is assumed that only this type of FC is used in the freight transport sector. Freight road vehicles, including both heavy and light commercial vehicles, employing hydrogen FCs are assumed to be on average 50 percent more efficient than similar vehicles employing ICE-based drivetrains (compared with 120 percent for cars in Figure 3-11).

3.3.4 New energy-carrier production technologies

3.3.4.1 Energy carriers

ERIS already incorporates a number of primary fuels (coal, oil, gas, biomass, uranium, renewables) that can be used either by electricity generation technologies or directly in end-use sectors. However, the disaggregation of the non-electric end-use sectors (so as to model transport, among other activities) requires a more detailed representation of secondary energy carriers. For example, hydrogen produced from coal can be used to supply end-use needs in the stationary, transport and electricity generation sectors. Accordingly, energy carrier production technologies for hydrogen (from coal, gas and biomass), alcohols (from gas and biomass) and petroleum products (from crude oil and coal)[25] were incorporated into the model, as was an energy balance for each carrier. Details of the costs and components used in some energy carrier production technologies are discussed in Appendix C.

One notable exclusion from the ERIS model during this stage of development is technologies for hydrogen production with electrolysis, mainly because it is assumed to be too expensive (based on Simbeck and Chang 2002). This assumption follows logically from other assumptions about the cost of electricity generation technologies compared to H_2 production technologies using the same feedstock, and transmission and distribution costs for either carrier.[26] However, for later analysis in Chapter 7, the synthesis of hydrogen via electrolysis

[25] For example, see SASOL 2005.

[26] For example, the capital and operating costs and characteristics used in the model (Kypreos *et al.* 2000; Barreto and Kypreos 2000, 2004a; Appendix B) mean that 1 MWh of electricity from gas combined-cycle generation is more expensive than 1 MWh of H_2 produced from steam methane reforming of natural gas. This is the case across all fuels, including renewables, and is maintained even under extreme technological learning assumptions that favour electricity generation. The operating characteristics of H_2 production and electricity

using baseload electricity generation was included. As discussed in Chapter 7, however, the level of deployment of this technology was observed to be negligible, consistent with the assumptions outlined above. Nevertheless, it should be noted that H_2 production using electrolysis may still be suitable for certain niche markets, such as in geographically isolated areas without indigenous fossil fuel or biomass sources but with access to other renewables (although the level of geographical detail in ERIS is not sufficient to address these specific niches).

3.3.4.2 Fuel transmission and distribution infrastructure costs

In addition to modelling fuel extraction and secondary energy carrier production and processing, ERIS was extended to include transmission and distribution technologies. These technologies convey primary and secondary fuels (energy carriers) to the site of final demand. The cost of the infrastructure required to transport these fuels may have a bearing on the choice of fuel for a particular application, except in cases where final demand can only be met by a single fuel. Where different energy carriers compete to supply energy demand (such as in stationary direct fuel use or transport), the costs of distributing different fuels or energy carriers may vary widely, and this may affect the relative competitiveness of the different fuels. For example, hydrogen may compete with petroleum in supplying transport energy demand, but these two fuels rely on separate delivery systems, the cost of which will affect the relative price of hydrogen and petroleum to final consumers.

To account for these factors, transmission and distribution infrastructure costs were incorporated into the ERIS model based on those used in the MESSAGE model (Riahi 2003) and on estimates reported by Ogden *et al.* (2004). Moreover, the economies of scale in pipeline and other transmission and distribution systems are also incorporated through specification of higher initial costs (based on Ogden 1999; Amos 1998).

These modifications to the ERIS model, along with others presented above in Section 3.3.3 and the remainder of Section 3.3.4, provide much of the basis upon which transport technologies can be studied within the context of the energy system. As an illustration of the applicability of the ERIS model to studying sustainable automobility, Box 3-1 presents the GHG emissions implications for a selection of combinations of the transport technologies, fuels and fuel production routes discussed in Sections 3.3.3 and 3.3.4.

3.3.5 Calibration of the model to the year 2000

The model base year was set to 2000 and calibrated to International Energy Agency (IEA 2003a,b; Argiri 2003) data on energy production, trade, consumption, electricity generation and capacity, and OECD data on transport fuel efficiency (Landwehr and Marie-Lilliu 2002).

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generation mean that H_2 production is more efficient and also more amenable to CCS, indicating that GHG taxes are also expected to favour H_2 production over electricity generation.

Box 3-1 Suitability of the ERIS model for exploring sustainable automobility

The model expansions and improvements presented so far represent a number of key elements in the overall policy and scenario assessment framework developed in this dissertation. Moreover, the combination of vehicle technologies, fuel synthesis pathways, primary resources and abatement technologies in ERIS provides a means by which to explore many energy-chain combinations for supplying demand for transport (and energy). Given the second theme of this dissertation, a brief snapshot of some of the possible fuel and engine technology combinations, and the implications for sustainability, is shown in Figure B-3-1. This figure presents different technology-fuel-production combinations and the resulting tank-to-wheels CO_2 emissions (i.e., the emissions produced directly from driving the vehicle) and partial well-to-tank emissions, comprising emissions from fuel conversion (synthesis and refining) and distribution, and sequestration. Sequestration is discussed in Section 0, and in the case of Figure B-3-1 includes both terrestrial sequestration via uptake in vegetation used as energy biomass, and geological sinks via carbon capture and storage (CCS).

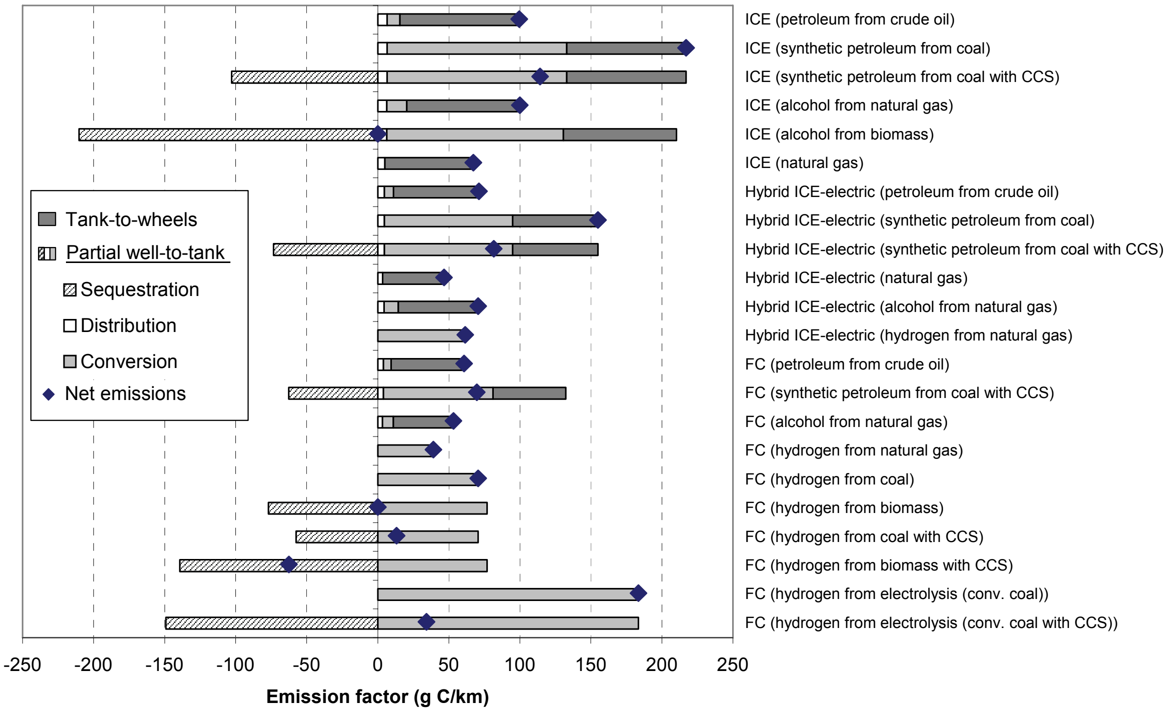

Figure B-3-1 Illustrative carbon emissions for different passenger transport energy chains in the ERIS model, North America (NAM) world region 2000-2010.

Abbreviations are as follows: ICE—internal combustion engine; FC—fuel cell; CCS—carbon capture and storage.
Note: in Figure B-3-1 net geosequestration emissions (CCS) are presented on the basis that the additional electricity needed to run the CCS plant is generated in a conventional coal power station.

It should be noted that Figure B-3-1 does not include well-to-tank emissions from sources such as fertilisers used for biomass production, transport of biomass, coal, oil or gas, or non-CO_2 emissions, although the latter are included in the ERIS model. Further, to restrict the number of combinations, the figure was constructed on the basis that all fuel requirements for conversion are supplied using the input or output fuel (rather than a third fuel). This explains why, for instance, net emissions from biomass-based synthesis are close to zero, because under the assumptions used here all energy requirements are supplied from zero-emissions biomass. Another important point to mention is that the information in Figure B-3-1 is based on ERIS model assumptions for the entire vehicle fleet in North America at the beginning of the 21st century. Technologies and efficiencies vary between regions, and are expected to improve significantly over the century.

(Box 3-1 continued)

Clearly, even with the restricted range of technologies and fuel combinations presented in Figure B-3-1, it is apparent that a number of technology options may play a role in a future sustainable transport system, but it is uncertain which will be most attractive, or how the transition may unfold. The ERIS model provides a means by which to consider not only the characteristics of transport technologies and transport fuels, but also the competing demands for these fuels which may affect the possible emergence of a sustainable passenger transport system. For example, although Figure B-3-1 shows that hydrogen has the potential to play a major role supplying future road transportation energy needs in a sustainable way, it must be considered that hydrogen is a highly flexible energy carrier for which non-transport sectors are likely to compete, particularly as fuels such as gas and oil become scarce. Similarly, Figure B-3-1 also identifies alcohol fuels from biomass as a promising future transportation fuel compatible with sustainable-development goals, however the limited availability of biomass may mean that greater economic and environmental benefits can be derived by using biomass in other sectors. The effect of such competing demands, and the many other factors discussed so far, on future transport technology choice is examined in detail in the following chapters.

3.3.6 Technology learning in ERIS

New technologies may play an important role in overcoming some of the challenges to long-term sustainable development associated with the energy system. These technologies may include, on the one hand, those that represent a significant departure from today's fossil-based systems, and which may be well-suited for the very long-term. On the other hand, there may also be "bridging" technologies that are still compatible with the currently dominant structure of the global energy system, but able to pave the way for the transition towards a sustainable energy future. However, many technologies in either of these categories lack producer and market experience, and currently may be more costly than incumbent alternatives. Importantly, the competitiveness of these new technologies may be improved through so-called "technology learning", an important mechanism of technological change in the energy system. Learning may arise as a by-product of experience gained in making and using a technology, and together with the impact of economies of scale may significantly reduce future costs (see e.g., Nakićenović 1997).[27] This is evidenced by the fact that some technologies experience declining costs as a result of their increasing adoption in the marketplace and/or of R&D efforts (see Section 2.2.1 in Chapter 2).

Accordingly, the endogenisation of technology learning in the ERIS model is essential in order to reflect the potential long-term impact of new technologies that may radically transform the energy system. This is also important for better representing the impact of alternative policy instruments and technology deployment, and the subsequent impact of technology diffusion on sustainable development in the areas of climate change, security of energy supply and transportation, among others.

The ERIS model used in this dissertation considers single-factor learning curves (1FLCs), where cumulative installed capacity is used as a proxy for accumulated experience (Kypreos

[27] Costs may decrease as a result of increasing adoption into the society due to the accumulation of knowledge by, among others, learning-by-doing, learning-by-searching, learning-by-using and learning-by-interacting processes. These effects can be represented with learning curves. For a discussion of learning curves see e.g. Argote and Epple (1990), IEA (2000) or McDonald and Schrattenholzer (2002); the latter two in the context of energy technologies.

et al. 2000).[28] The typical formulation of one-factor learning, or experience, curves describes the specific investment cost of a given technology as a function of the cumulative capacity—a proxy for experience (Argote and Epple 1990). The experience curves attempt to represent the fact that some technologies experience declining costs as a result of their increasing adoption due to, among others, learning-by-doing (manufacture) and learning-by-using (use) effects. The specific investment cost (SC) is formulated as:

$$SC_{te,t} = a' \bullet CC_{te,t}^{-b} + floor_{te} \qquad (1)$$

where: $SC_{te,t}$ is the specific cost of the technology; $C_{te,t}$ the cumulative capacity; $floor_{te}$ the technology floor cost; a', the specific cost at unit cumulative capacity; and, b, the learning-by-doing index.

Usually, instead of the learning index b the learning rate (LR), i.e. the rate at which the cost declines each time the cumulative production doubles, is specified as follows:

$$LR = 1 - 2^{-b}$$

For instance, a LR of 10 percent means that costs decline by 10 percent for each doubling of cumulative capacity.

As mentioned at the beginning of Section 3.3, the ERIS model can be represented by a system of simultaneous equations reflecting engineering and economic relationships within the energy and transport system. However, the inclusion of non-linear equations simulating learning, such as the specific investment cost equation above, renders the ERIS model itself non-linear. This non-linearity, and likely non-convexity,[29] raises computational difficulties in solving the model (i.e., by finding the global minimum of a particular variable, such as energy system cost). Accordingly, for the 1FLC representation, a piece-wise linear approximation of the learning curve is obtained through Mixed Integer Programming (MIP) techniques. The MIP approach provides a linearisation of the original non-linear, non-convex problem and allows identification of an optimum for the approximated problem, although at a higher computational cost. For a description of the MIP approach in ERIS see Barreto (2001) or Kypreos *et al.* (2000).

Typically, when optimisation models with perfect foresight, such as ERIS, endogenise technology learning, it may become cost-effective for the model to make higher, early investments in initially expensive technologies if they exhibit sufficient cost reduction potential along the time horizon. This modelling result highlights the fact that, from a long-term perspective, it could be sensible to invest today in the learning process of promising technologies that could become competitive in the long run.

3.3.6.1 Development of a "key technologies" approach to technology learning

The formulation of learning in ERIS, as described above, was implemented previously by Barreto (2001) and Kypreos *et al.* (2000). Their version of ERIS was specified with a number of learning technologies that were identical to specific energy conversion or end-use

[28] An earlier version of ERIS also modelled two-factor learning curves, where cumulative capacity and a knowledge stock function are used to represent market experience (learning-by-doing) and knowledge accumulated through R&D activities (learning-by-searching), respectively (Barreto and Kypreos 2004a,b).
[29] That is, the existence of more than one local optimum.

technologies. For example, advanced coal-based electricity generation with integrated gasification combined cycle (IGCC) systems was considered both an electricity generation technology and a learning technology, with specific investment costs declining as a function of installed capacity (learning-by-doing) and R&D (learning-by-searching). Consequently, each energy conversion or end-use technology learned independently, even though some had components common with other technologies and would be expected to benefit from learning in those other technologies.

To improve this simplified representation of learning, a number of modifications and extensions have been incorporated as part of the work in this dissertation, the most significant of which is the implementation of a clustering approach to learning. The idea of technology clusters has been applied in several modelling approaches (Gritsevskyi and Nakićenović 2000; Seebregts *et al.* 2000) and is based on the fact that a technology does not evolve alone but in interaction with other technologies, infrastructures, institutions, networks of actors, etc. (see also Section 2.2.1 in Chapter 2). This "technological proximity" may stimulate a collective co-evolution process. Technological clusters are shaped when related technologies interact and cross-enhance each other, contributing to their mutual development (Nakićenović 1997). As part of the clustering process, spillovers of learning between technologies can occur, as related or complementary technologies benefit from the learning processes of each other (Grübler *et al.* 1999; Gritsevskyi and Nakićenović 2000).

Following Seebregts *et al.* (2000), the concept of a "key technology" was implemented in ERIS to represent some aspects of technology clusters. A "key technology" is defined as one that is a component of several other technologies specified in the Reference Energy System (RES) (see Figure 3-10 above)—for example, the gas turbine is a key technology used in integrated gasification combined cycle (IGCC) coal, gas combined-cycle and single-cycle gas turbine electricity generation plants. For each key technology (hereafter referred to as a component), a learning curve is specified in ERIS. The technologies that use this component are then grouped in a sub-cluster in such a way that installation of any one of the technologies in the sub-cluster results in learning-by-doing in the common component, benefiting all technologies in the sub-cluster. It should be noted that the term sub-cluster is used to more narrowly specify technology clusters—defined in Chapter 2 (Section 2.2.1)—focusing on related technologies, rather than infrastructures, institutions and other networks. Importantly, ERIS also includes a representation of infrastructures and complementary technologies (see Sections 3.3.2 and 3.3.4), and the systems engineering approach already ensures these cluster elements are well-represented in the modelling framework.

With the above approach to sub-clusters it is also possible to incorporate more complicated learning spillovers into ERIS by splitting key components into smaller sub-components. This was done for the fuel cell, which was split into: 1) a generic fuel cell component that represents system components that are common to both stationary and mobile fuel cells; and 2) a stationary fuel cell component that is used only by the stationary sector.

Another benefit of applying this "key technologies" approach to the ERIS model is that it rationalises the number of learning technologies, allowing a larger and more realistic number of technologies to improve through learning, without significantly increasing model solution times.

3.3.6.2 The learning components

The learning components incorporated into the ERIS model comprise:

- generic fuel cell,
- stationary fuel cell,
- gasifier,
- gas turbine,
- steam reformer,
- carbon adsorption,
- hybrid battery/control system,
- advanced nuclear reactors,
- photovoltaic plants,
- wind turbines, and
- advanced direct gas combustion.

The last four components listed above correspond directly to learning technologies included in earlier versions of ERIS—that is, advanced nuclear, solar PV, wind and direct gas combustion. Details on the costs of the new components are discussed in Appendix B3 (transport technologies) and Appendix C (others). Simple one-factor learning curves for each of these components currently incorporated in the model are presented in Appendix D.

These components are used in 26 technologies, allowing extensive learning-by-doing possibilities. These 26 learning technologies comprise:

- 8 electricity generation technologies;
- 6 energy carrier production technologies;
- 7 passenger car technologies;
- 4 carbon capture and storage technologies; and
- 1 direct-use stationary sector technology.

Table 3-4 presents the relationship between the technologies and key learning components.

Consistent with the focus of the second theme of this dissertation on transport, the potential impact of learning over the long term on automobile drivetrain technology costs (presented in Appendix B3) is illustrated in Box 3-2 which presents a comparison of the competitiveness of alternative vehicle drivetrains accounting also for upstream fuel production and distribution costs.

Table 3-4 Learning components and technologies

Technologies			Learning components										
			FC fuel cell	SFC stationary fuel cell	GT gas turbine	GA gasifier	SR steam or autothermal reformer	AN advanced nuclear	AP PV plants	AW wind turbines	HY hybrid battery system	CA absorption and stripping (SELEXOL)	AG gas non-electric
Electricity generation	HCC	Conventional coal											
	HCA	Advanced coal			×	×							
	OLC	Conventional oil											
	GCC	NG combined cycle			×								
	GSC	Gas steam cycle											
	GTR	Gas turbine			×								
	GFC	Gas fuel cell	×	×			×						
	BIP	Biomass power plant											
	NUC	Nuclear conventional											
	NNU	New nuclear						×					
	HYD	Hydro											
	STH	Solar thermal											
	STC	Solar thermal cogen											
	SPV	Solar PV							×				
	WND	Wind								×			
	ORE	Other renewables (geothermal etc.)											
	HEF	Hydrogen fuel cell	×	×									
Non-electric stationary	GASNE	Gas non-electric											×
	COALNE	Coal non-electric											
	OILNE	Oil non-electric											
	BIONE	Biomass non-electric											
	SALNE	Alcohol non-electric											
	SH2NE	Hydrogen non-electric											
Heat techs	COALDHN	Coal district heating											
	GASDHNE	Gas district heating											
	OILDHNE	Oil district heating											
	BIODHNE	Biomass district heating											
	STHDHNE	Solar thermal heating											
	OREDHNE	Geothermal heating											
Fuel synthesis	OILREF	Conventional oil refining											
	SYNFNE	Fisher-Tropsch from coal				×							
	BIOALNE	Alcohol from biomass				×							
	GASALNE	Alcohol from gas					×						
	GASH2NE	Hydrogen from gas					×						
	COALH2NI	Hydrogen from coal				×							
	BIOH2NE	Hydrogen from biomass				×							
Carbon capture	HCACS	Capture from advanced coal electricity generation and F-T fuels production										×	
	HCCCS	Capture from conventional coal										×	
	GCCCS	Capture from GCC										×	
	H2CAS	Capture from hydrogen production										×	
Cars	ICC	Internal combustion conventional											
	ICG	Internal combustion gas											
	ICA	Internal combustion alcohol											
	ICH	Internal combustion hybrid									×		
	IGH	Internal combustion gas hybrid									×		
	IAH	Internal combustion alcohol hybrid									×		
	IHH	Internal combustion hydrogen hybrid									×		
	HFC	Hydrogen fuel cell	×								×		
	PFC	Petroleum fuel cell	×				×				×		
	AFC	Alcohol fuel cell	×				×				×		
Air	AIRC	Air transport conventional											
	AIRH	Air transport hydrogen											
Other transport	COALTR	Other transport - coal											
	GASTR	Other transport - gas											
	OILTR	Other transport - oil											
	ALTR	Other transport - alcohol											
	H2TR	Other transport - H2											

Note: Shading indicates a learning technology, and a cross indicates membership of the cluster corresponding to the component in the column heading.

Box 3-2 Learning and well-to-wheels car transportation costs

Figure B-3-2 presents a comparison of the *technology-dependent* cost per kilometre broken down by car technology, fuel production and fuel delivery costs for one region (North America). The full impact of learning-by-doing in car technologies, based on the costs and learning rates in Appendix B3, has been assumed in the calculation of the costs in Figure B-3-2. That is, the more advanced technologies such as HEVs and FCVs are initially significantly more costly than indicated in the figure. Importantly, the figure does not report direct refueling costs, although the additional refueling costs of alternative fuels compared to petroleum are included in the fuel transmission and distribution costs.

Based on this simple comparison, the cheapest technologies are the natural gas (ICG) and conventional petroleum ICE (ICC), followed closely by the hybrid natural gas (IGH) and petroleum ICE (ICH), with the cheapest fuel cell vehicle coming roughly sixth. The dotted region at the top of each column in Figure B-3-2 shows the impact on costs of obtaining oil and natural gas from more expensive resource categories as defined by Rogner (1997), presenting the lower of either the additional cost of the more expensive fuel or the additional cost of switching to a different feedstock (coal or biomass). With higher resource costs the hybrids swap places with the conventional ICE technologies, in terms of costs, and the hydrogen fuel cell vehicle (HFC) becomes a close competitor to the cheapest technologies.

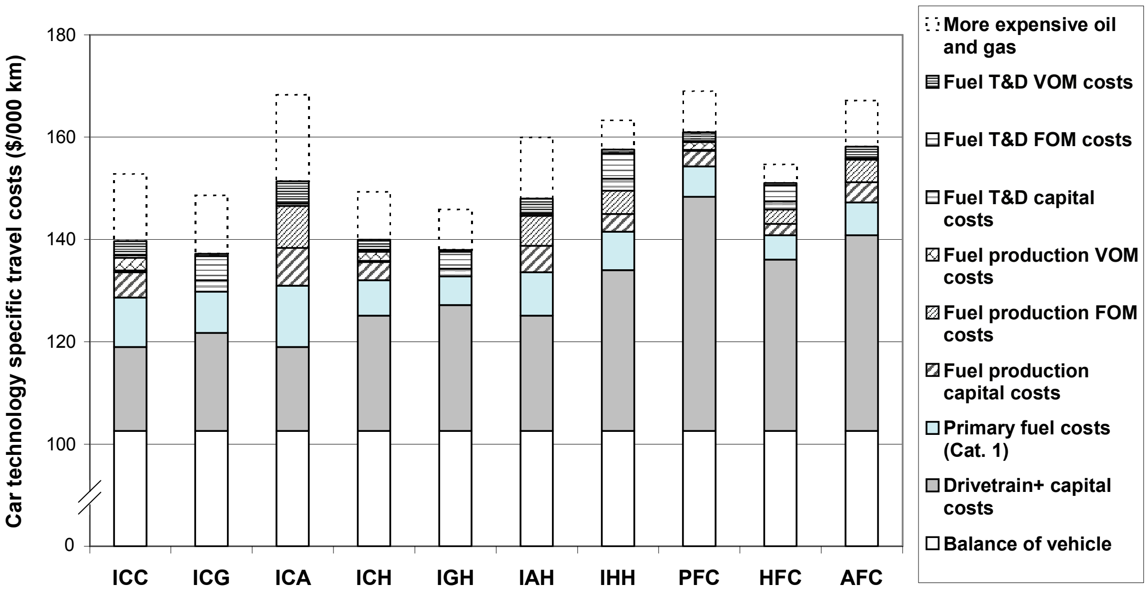

Figure B-3-2 PMV travel costs, assuming full technological learning (i.e., components at floor costs), North America

Note: see Figure 3-11 for definitions of technologies.

Importantly, this is a static and contrived analysis ignoring other end-use sectors and technologies, and can only provide some basic information about which vehicle technology-fuel combinations may be the most competitive in the future. The analyses in later chapters in this dissertation explore this question much more comprehensively, although it should be remembered that future technology costs are uncertain.

3.3.7 Modelling impacts on global climate

3.3.7.1 Addition of emissions and abatement options

The preceding sections of this chapter have described in detail scenario development, and modelling of the energy system and technology learning. To fully exploit this framework for analysing sustainable development, it is also necessary to incorporate into the ERIS model additional information on greenhouse gas (GHG) emissions, given their role in the threat of climate change.

The inclusion of comprehensive energy system detail and global coverage in ERIS already enables the straightforward calculation of energy-related CO_2 emissions. Accordingly, the model extensions described here deal with the incorporation of GHGs other than CO_2 from energy, namely the two other main gases, methane (CH_4) and nitrous oxide (N_2O). Although CO_2 is the largest historical contributor to climate change and will most likely continue to have a very important relative role in the future, anthropogenic emissions of CH_4 and N_2O make a significant contribution to radiative forcing and climate change (IPCC 2001a).

The ERIS modelling framework was extended to endogenise the three main GHGs, although with a focus on the contribution of the global energy system. The incorporation of CH_4 and N_2O is an important addition when examining cost-effective strategies for mitigation of global climate change. Specifically, considering the high global warming potentials[30] of CH_4 and N_2O, multi-gas mitigation strategies are likely to be cost-effective compared to CO_2-only abatement (Rao and Riahi 2005).

Emissions of sulfur dioxide (SO_2) have also been included because oxidation of this gas produces sulfate aerosols (SO_4^{2-}) which can also have a significant impact on the climate. These aerosols tend to produce a cooling effect, both directly through reflecting solar radiation into space and indirectly through their impact on clouds (Hulme *et al. 2*000).

i) Methane and nitrous oxide

Projections of regional emissions of the main non-CO_2 gases to 2020 were obtained from the EPA (2003). These emissions were incorporated into the ERIS model using two approaches to project beyond 2020, depending on whether the emissions could be linked to other model variables.

Emissions associated with the mining of coal and the extraction of oil and natural gas were linked endogenously to the production levels of each fuel in the model, based on estimates from the EPA (2003) and fuel production figures from the IEA (2003a,b). The remaining non-CO_2 emissions are included exogenously and, because of the high uncertainty associated with future emissions from sources such as agriculture, these emissions are simply extrapolated linearly beyond 2020.

Abatement cost curves for CH_4 and N_2O emissions from a number of sources for 2010 and 2020 were obtained from the EPA (2003).[31] These were extrapolated to 2100 for each source assuming that the proportion of emissions that can be abated for a given cost is independent of

[30] That is, the higher relative contribution to radiative forcing of CH_4 and N_2O compared to CO_2—assumed here to be 21- and 310-times greater, respectively.
[31] For applications of the abatement curves see, for instance, Reilly *et al.* (1999, 2002) or de la Chesnaye *et al.* (2001).

the absolute level of emissions. That is, if 20 percent of the emissions from landfills can be abated for US$20/ton of carbon-equivalent (tC-e)[32] in 2020, then it is assumed that 20 percent of the emissions from landfills in 2050 can be abated for the same cost. A representative abatement cost curve is presented in Figure 3-12.

At the time of writing, abatement cost curves were not available for a number of significant sources—notably enteric fermentation and agricultural soils—and it is conservatively assumed that there are no significant abatement opportunities associated with these activities. This may be overly pessimistic, although on the other hand it may represent a prudent approach considering the high level of uncertainty regarding these emissions, and hence that it may be unwise to rely heavily on abatement opportunities associated with these sources.

In addition, CO_2 emissions from cement production were also incorporated into ERIS, as an exogenous factor linked to industrial thermal energy demand.

ii) Sulfur dioxide emissions

Emissions of sulfur dioxide were linked endogenously to consumption of hard coal. Initial coefficients were calculated using the EDGAR database (version 3.2, see Olivier and Berdowski 2001) and IEA (2003a,b) statistics, and assumed to decrease and converge across world regions by 2100. In addition, it is assumed that sulfur is effectively scrubbed from the emissions arising from coal-based hydrogen and synthetic fuel production, and in advanced gasification-based electricity generation plants (e.g., IGCC).

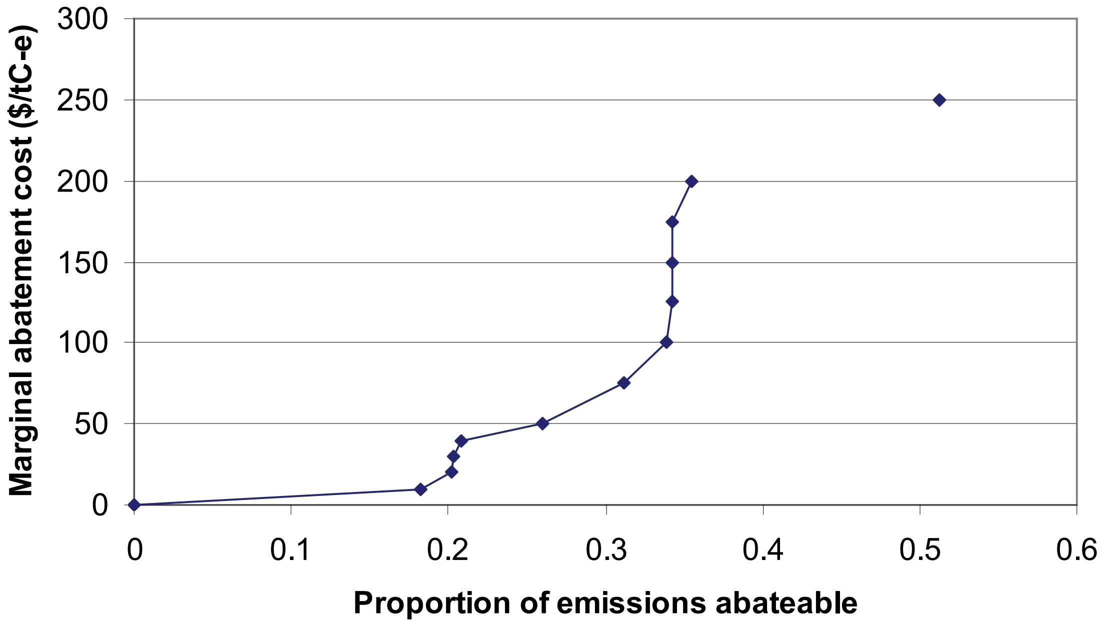

Figure 3-12 Marginal abatement cost (MAC) curve showing proportion of CH_4 emissions from natural gas production abatable for different costs, Western Europe 2020

Source: Original data are from EPA (2003)

Note that the most upper right data point represents the total abatement possible above US$200/tC-e. MACs for this and a number of other sources have been incorporated in the ERIS model.

[32] The unit ton refers here to metric ton.

3.3.7.2 Inclusion of geological and terrestrial sequestration

The application of carbon capture and sequestration technologies facilitates the use of carbon-rich primary energy sources while potentially reducing net emissions to the atmosphere. There are two basic possibilities for carbon sequestration: preventing the emissions from human activities reaching the atmosphere; and removing carbon from the atmosphere (Socolow 1997; DOE 2003). ERIS was modified to incorporate both alternatives.

i) Carbon capture, geological storage and leakage

A number of carbon capture technologies were added to ERIS to better represent abatement options. These capture technologies have been defined as add-ons to various emitting technologies and their costs (capital and operating) and energy requirements vary depending on the additional components required (see David and Herzog 2001, 2000; and Appendix C). The range of technologies in ERIS which are amenable to capture of carbon include hydrogen and synthetic fuels production, conventional (steam) and advanced (IGCC) coal electricity generation, and gas combined cycle and fuel cell electricity generation.

The captured carbon is assumed to be stored in geological formations, with a small but significant volume of leakage assumed (0.5 percent per annum), to represent some of the risks of this technology.

ii) Forest sequestration

Terrestrial biosystems represent the second major potential sink for CO_2 and are also included in ERIS. The potential for and cost of sequestration in forest sinks was derived from the TAR (IPCC 2001c, Sections 4.3 and 4.5) and Reilly *et al.* (2002). Restrictions on the growth in carbon sinks, and limits on the total sequestration are also represented in the model.

3.3.7.3 Linkage to the MAGICC climate model

As discussed in Chapter 2, energy and transport systems may pose a substantial threat to the realisation of sustainable development over the long term, given their major contribution to anthropogenic greenhouse gas emissions and climate change. In order to estimate the impact of GHGs from energy production and use, and from other sources, on indicators of climate change, the ERIS model has been linked to the stylised climate change model MAGICC (version 4.1, Wigley 2003) developed by Wigley and Raper (1997) and also described in Hulme *et al.* (2000). MAGICC models the impact of all the major greenhouse gases and the effects of regionalised fossil fuel-derived SO_2 emissions (on the level of three world regions). This linkage facilitates assessment of the impact on climate change of various policies and measures that affect the energy system, and therefore represents an important element in the policy analysis tool described in this dissertation.

The ERIS model generates inputs to MAGICC of energy-related CO_2 emissions (minus geosequestration), CO_2 emissions from cement production, CO_2 sequestration in forest sinks and comprehensive emissions of CH_4 and N_2O. Other emissions are exogenously specified, including emissions of halocarbons, sulfur hexafluoride (SF_6), non-N_2O oxides of nitrogen (NO_x), volatile organic compounds (VOCs) and carbon monoxide (CO), and net emissions from deforestation. Estimates of these emissions were taken from the IPCC/SRES B2 scenario and are assumed to be independent of energy system characteristics (Nakićenović and Swart 2000). The linkage between the energy-systems ERIS model and the climate change MAGICC model is presented in Figure 3-13.

It should be noted that the analysis in this dissertation does not seek to assess the ultimate impacts of climate change, such as increased flooding, crop failures, losses of biodiversity and increased mortality, given the high levels of uncertainty (IPCC 2001a,b). Instead, it is assumed that the risk of these impacts is of sufficient severity that mitigation and adaptation to climate change must constitute a critical element of any transition to sustainability in the long term. Further, except for the impact of temperature on the terrestrial carbon cycle, the linked ERIS-MAGICC model does not consider feedbacks from climate variables to driving forces, such as those discussed in Chapter 2 and in Section 3.2.

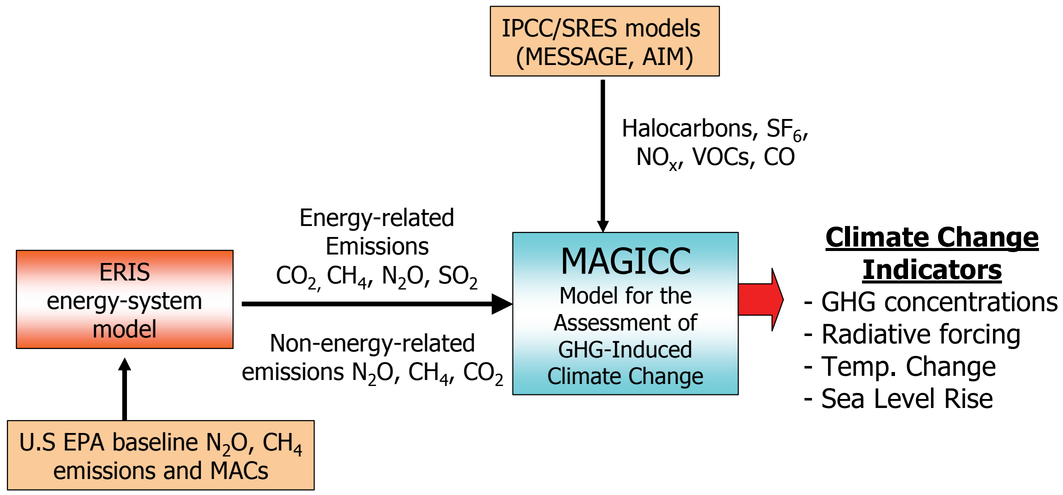

Figure 3-13 Linkage between the energy-systems ERIS model and the climate change MAGICC model

3.4 Summary and concluding remarks

One of the main objectives of the work described in this chapter was to construct the core of a policy analysis tool for improving understanding of the challenges associated with realising sustainable development, and exploring the emergence of a sustainable energy and transport system (particularly in terms of overcoming the threats posed by future demand for automobile transport). With this objective in mind, this methodological chapter documents the changes made to ERIS, a "bottom-up" energy-systems optimisation model that endogenises learning curves, to enable it to address critical elements of sustainability—including economic development, climate change, and security of energy supply.

Since these key elements of sustainable development are closely related to energy production and consumption, one fundamental requirement was to ensure ERIS represents comprehensively the global energy system. To this end, to the existing electricity sector detail in the ERIS model were added details for several non-electric sectors, covering transportation and thermal needs, and corresponding technologies. In addition, fuel production technologies were included, specifically for hydrogen, alcohols and Fischer-Tropsch liquids. Furthermore, a clusters approach to the representation of technologies was developed, whereby different technologies sharing a common "key learning component" benefit from learning spillovers.

Another important feature of the analysis tool presented in this chapter is its ability to represent the relationship between the energy system and climate change. The first step in representing this relationship involved adding emissions estimates and marginal abatement curves for the two main non-CO_2 greenhouse gases (CH_4 and N_2O) and forest sinks to the ERIS model, in addition to CO_2 capture and storage technologies. Furthermore, the ERIS model was linked to MAGICC, a simplified climate model, creating a framework capable of examining linkages from technology choice in energy systems through to key global indicators of climate change. Moreover, the combined ERIS-MAGICC framework goes some way towards realising one of the objectives of this dissertation to develop a policy analysis tool, by facilitating the examination of the impact of various policy instruments in stimulating technological pathways that may promote the emergence of a low-emissions energy system over the long term.

Other elements of sustainable energy development, such as security of the energy supply, are addressed in the ERIS framework through the inclusion of regional disaggregation of energy production, consumption and resources. In addition, the time horizons that ERIS is suitable for modelling are sufficiently long to fully explore the role of energy in development, and the challenges that may arise as today's developing countries achieve high income levels. This long timeframe is also necessary for analysing climate change and longer-term security of energy supply.

Further, in view of its importance to policy makers, and to address the second theme of this dissertation focusing on sustainable automobile transport, special attention has been given to the representation of the passenger vehicle sector, allowing a more comprehensive investigation of possible technological transitions in the car sector and the associated energy-supply systems over the long term.

Accordingly, the ERIS model framework described in this chapter fulfills many of the requirements of a policy analysis tool for exploring sustainable development. In Chapter 6 the inclusion of additional features, such as feedbacks between the energy system, economy and transport sector is described.

In addition to the model description, this chapter also discussed the selection and construction of a scenario for exploring sustainable development, including elements encompassing economic growth and partial convergence between industrialised and developing countries, regional resource estimates, and future passenger transport demand. The following chapter presents the application of the ERIS policy analysis tool to this scenario to examine possible automobile technology and fuel trends over the 21st century, including the impact of technology learning and climate change policies.

Chapter 4. Automobile technology, hydrogen and climate change: an application of the analysis framework

4.1 Introduction

The transitions that could take place in the global automobile sector in the course of the 21st century are uncertain. Fuel cell and hybrid-electric vehicles (hereon referred to as FCV and HEV, respectively) could be serious challengers to the currently dominating internal combustion engine vehicle (ICEV) in the long term, particularly if sustainable development becomes an increasingly important social concern. However, how a transition from the ICEV towards the FCV and/or HEV could unfold is unknown.

Also, it is not clear which energy carriers would play a role in the long term. Several energy carriers could substitute for the today's dominant oil products, which have well-known environmental and geopolitical problems that make them incompatible with longer-term sustainable development. Among others, hydrogen (H_2) has been identified as an attractive alternative for the long run, in particular if used in fuel cells (FCs). However, there are major challenges associated with the introduction of hydrogen including costs, infrastructure development and deployment of production, storage and end-use technologies.

Combined with these uncertainties is an expectation that transport activity will experience rapid growth over the 21st century as incomes in developing countries rise (see Section 3.2.1 in Chapter 3), with a concomitant increase in energy consumption. In passenger transport, without either a substantial reduction in demand for mobility or a shift towards public transportation (mass transit), both of which run counter to current global trends, attenuating this growth in energy demand requires switching to advanced engine technologies.

However, the availability, cost and performance of the technologies that may underpin future transitions in the evolution of transportation and energy systems are affected by the always-active force of technological change. Although uncertain in pace and direction, the cumulative and pervasive effects of this force could transform substantially the suite of technologies that serve our mobility needs and the systems that supply energy to them in the long term (for a discussion, see e.g. Nakićenović 1991; Ausubel *et al.* 1998). Moreover, transitions in the energy and transportation sectors are likely to span long periods of time, due to the large inertia of technological systems. In general, the introduction of technologies and energy carriers that are not compatible with the dominating technological regime can be very difficult (Kemp 1997a; Kemp 1997b). Often targeted investments in research and development (R&D), focused demonstration projects and early deployment strategies are necessary to enable emerging technologies to become cost-effective and competitive in the marketplace.

The prospects for H_2 and FCs in the private motor vehicle (PMV, or car) sector are often discussed in the context of the "hydrogen economy", i.e. a global energy system where H_2 becomes one of main final-energy carriers. The "hydrogen economy" is receiving increasing attention as an attractive alternative to achieve sustainability goals in the energy sector (see e.g. Ogden 1999; Barreto *et al.* 2003). Fuel cells, with applications in both stationary and transport sectors, are seen as one of the key technologies that could drive a transition towards a "hydrogen economy". Given the potential of hydrogen, fuel cells and other technologies to contribute to a more sustainable energy and transport system, exploring strategies that could facilitate their introduction is an important exercise for identifying appropriate policy and investment targets, particularly since major barriers exist for a number of these technology options.

As discussed in Chapter 2, a key driver of the development of the global energy system in the long term is the need to substantially reduce the emissions of greenhouse gases (IPCC 2001c). Within this context, there has been a substantial debate on the role of H_2-powered FC cars in a strategy to mitigate GHG emissions (see e.g. Keith and Farrell 2003; Azar *et al.* 2003). It has been argued that mitigation of climate change, among others, could be a reason to support the early introduction of H_2-powered FC cars, especially given the expected rapid increase in personal mobility in the developing world. However, it appears more likely that, in the short term, sectors other than transportation (e.g. electricity generation and non-CO_2 gases) may be the main targets for curbing GHG emissions. Nonetheless, in the long term, the transportation sector should also evolve towards a low-emissions configuration. Accordingly, this chapter investigates how the imposition of a cost on greenhouse gas emissions affects technology choice in the passenger car sector. Specifically, we examine the potential role of FCVs and HEVs in future transport and energy systems, and the influence of the infrastructure barriers in the introduction of these technologies.

For this long-term analysis the ERIS (Energy Research and Investment Strategies) model and transport scenario described in Chapter 3 are applied. The "bottom-up" energy-systems optimisation features of the ERIS model, along with its representation of technologies and technology dynamics, enables us to examine the passenger car sector within the context of the global energy system. One of the chief advantages of using a comprehensive energy system model is the ability to account for competing demands for the fuels that may be used for transportation. For example, although much is made of the potential for H_2 to meet future road transportation energy needs, in reality the utilisation of H_2 is likely to be influenced by at least two forces independent of the progress of transport technologies: a) the need for fuel transmission and distribution infrastructure; and b) the fact that H_2 is a highly flexible energy carrier for which non-transport sectors (and transport sectors with fewer fuel switching options, such as air transportation) are likely to compete, particularly as fuels such as gas and oil become scarce. Similarly, alcohols from biomass are also considered a possible future transportation fuel, but the limited availability of biomass may mean that greater economic and environmental benefits can be derived by using biomass in other sectors.

Further, a comprehensive model is extremely useful for comparing the cost-effectiveness of greenhouse gas abatement activities in different sectors, including transport.

The remainder of this chapter is organised as follows. Since the modelling framework is already described in detail in Chapter 3, we turn immediately to the results of the analysis in Section 4.2, which is divided into a number of sub-sections. Section 4.2.1 presents some selected results for a baseline case for meeting future passenger transport demand, with and without technological learning. In Section 4.2.2 the impact of a GHG-constraint is examined, while Section 4.2.3 examines the influence of infrastructure for H_2 delivery on the technology choices in the model. Finally, in Section 4.3 some conclusions and policy insights are outlined.

4.2 Results: transport technology deployment

To explore the potential of vehicle technology dynamics and deployment over the 21st century, three sets of scenarios are presented. These include:

- a baseline scenario where no technology or greenhouse policy instruments are implemented (with and without technological learning);

- a series of climate change mitigation scenarios where progressively higher carbon-equivalent (C-e) taxes are imposed on anthropogenic greenhouse gas emissions; and

- a “pro-H_2” scenario where it is assumed that, in addition to a low C-e tax, there is strong support for the development of H_2 delivery infrastructure, thereby reducing the transmission and distribution costs of this fuel.

The first scenario illustrates the impact of experience on the competitiveness and deployment of new vehicle technologies, and also forms a baseline for examining the impact of the subsequent scenarios. The second scenario is designed to illustrate the impact of broader abatement policies on the choice of transportation technologies and transport emissions, and also examine the relative cost-effectiveness of directing abatement activities towards the passenger car transportation sector. The third scenario is designed to investigate the impact of technology- (or fuel-) specific infrastructure support on future transport technology transitions. Delivery infrastructure was chosen as the target since the deployment of hydrogen distribution systems is one of the barriers often cited to the wider uptake of this fuel in small-scale applications such as PMVs.

These three sets of scenarios are designed to provide a preliminary indication of the possible role of advanced vehicle technologies and alternative fuels in the realisation of sustainable development—one of the themes explored in this dissertation. We return to the possible role of automobile technologies in sustainable development in more detail in Chapter 7. Moreover, the scenarios presented here also provide a means by which to illustrate and test the behaviour and potential advantages of the modelling framework and scenario constructed in Chapter 3.

All of the above scenarios are based on the future car transportation demand projection presented in Section 3.2.2 of Chapter 3. To recap, in this demand projection, car transportation is assumed to grow from roughly 9 trillion kilometres of travel in 2000 to around 37 trillion kilometres in 2100. Clearly, this growth has major social (in terms of urban planning, mobility), economic (infrastructure, congestion) and environmental (emissions, resource extraction) implications. As presented in Figure 3-6 (see Chapter 3), in this demand scenario most of the growth occurs in developing regions, with the industrialised regions returning to close to year 2000 demand by the end of the century. It is also worth noting that in this travel demand scenario, aggregate car transportation in developing regions surpasses that in the industrialised world in around 2040-2050. As discussed, this long-term stabilisation and decline of demand in industrialised regions can be attributed almost entirely to a shift to faster and more expensive modes of transportation as incomes rise, which itself has significant implications, in terms of resource consumption, pollution and infrastructure needs.

4.2.1 Technological learning and transportation technologies

Many new transportation and fuel production technologies are currently more costly than the conventional internal combustion engine and oil refinery because of limited experience, a current lack of economies of scale and technological immaturity. Conversely, increasing experience (i.e., learning) and achieving economies of scale is likely to reduce the future cost of these technologies. So, how much of an impact is this learning likely to have?

Figure 4-1 and Figure 4-2 illustrate the impact of learning-by-doing on the future choice of car technologies that minimises total discounted global energy system costs over the 21st century, using the ERIS modelling framework described in Chapter 3. Figure 4-1 presents a case where there is no learning-by-doing in any of the components used in transportation technologies. Learning-by-doing is assumed to occur, however, for components used only in stationary applications, such as gas turbines, gasifiers, stationary FCs, and advanced nuclear power generation (see Table 3-4 in Chapter 3). Figure 4-2 illustrates the impact on technology choice if we include the effect of learning from experience with important transportation technology components, comprising the mobile FC, reformer and hybrid battery system (see Table B-2 in Appendix B for technology learning characteristics). Importantly, the timing and speed of adoption of new technologies is affected by many factors, which include not only current and future technology costs, but also constraints on technology diffusion, resource availability and competing demands, and limits on how quickly new fuel production and distribution infrastructure can be deployed.

Based on the assumptions used here and in the absence of technological learning, ICEVs remain the dominant technology, although there is a shift towards increasing use of natural gas until resource depletion forces a shift back towards petroleum products at the conclusion of the century (see Figure 4-1). A very small number of natural gas HEVs also enter the market. Incorporating the impact of learning from experience into the projection (see Figure 4-2) results in the introduction of several technologies that were previously unable to compete. HEVs, in particular experience a relatively rapid uptake and dominate the automobile market by the end of the century. FCVs, on the other hand, account for less than 1 percent of the market by 2100. The direct H_2 FCV accounts for all of this uptake, it being the cheapest FC technology (see Box 3-2 in Chapter 3 for an illustrative cost comparison). As in the non-learning case, natural gas is the preferred fuel until late in the century when there is a shift back to petroleum HEVs in response to dwindling resources of cheap gas.

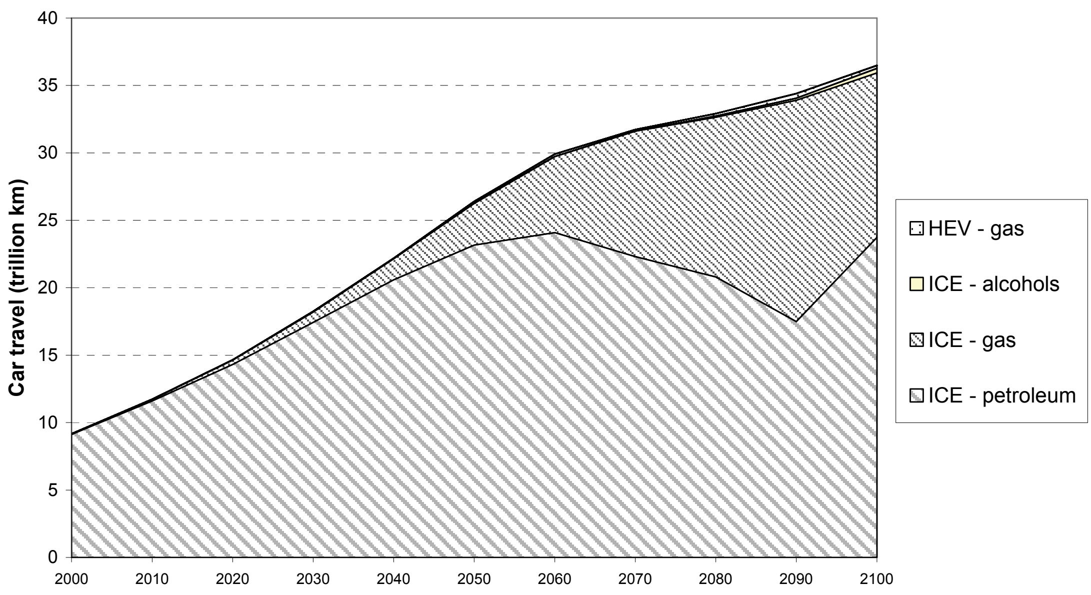

Figure 4-1 Global car travel by drivetrain technology and fuel (without learning in mobile FC, reformer and battery system), 2000-2100

Abbreviations are as follows: ICE – conventional internal combustion engine vehicle; HEV—hybrid ICE-electric vehicle; and FCV—hybrid fuel cell-electric vehicle.

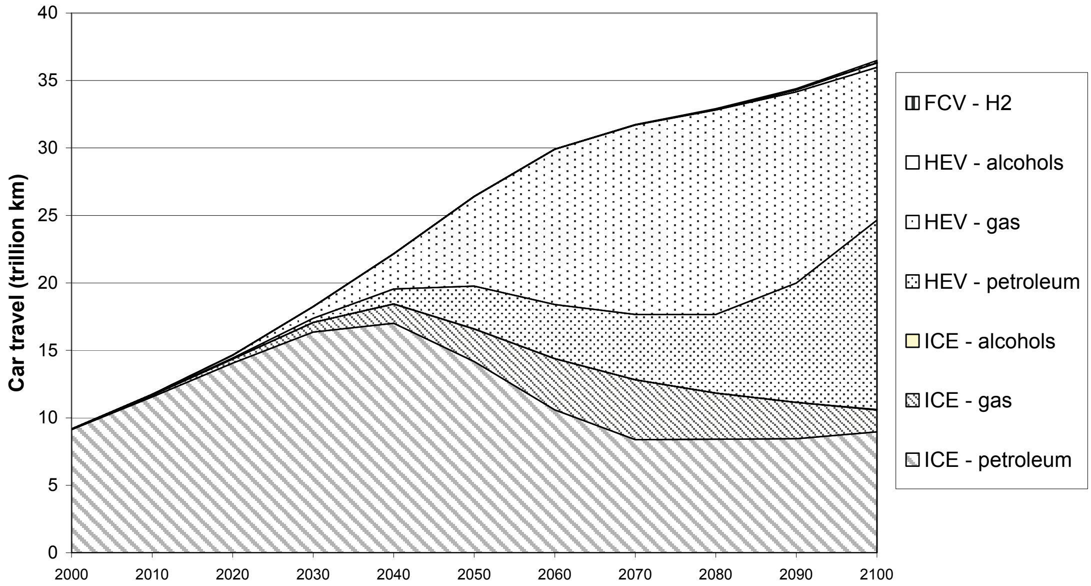

Figure 4-2 Global car travel by drivetrain technology and fuel (with learning-by-doing in mobile FC, reformer and battery system), 2000-2100

Abbreviations are as follows: ICE—conventional internal combustion engine vehicle; HEV—hybrid ICE-electric vehicle; and FCV—hybrid fuel cell-electric vehicle.

The transition to HEVs over the century in this scenario, and their eventual dominance, plays some role in supporting the development of FCVs. This occurs because the battery system used by the HEV is also assumed to be required in the FCVs and, accordingly, experience gained with HEVs helps to reduce the cost of this component of the FCVs. In this way, the HEV may act as a bridging technology between today's ICEV and FCV in the long run. Similarly, experience with stationary FCs in this scenario also benefits the FCV. By 2100 almost 2 TW of cumulative gas FC or direct H_2 FC electricity generation has been installed globally. Although, as discussed earlier in Section 3.3.6, there are only partial spillovers between stationary and transport FC applicants, this quantity is assumed to be sufficient to bring about a major reduction in mobile FC costs. The combined effect of the experience gained with HEVs and stationary FC technologies, however, does not appear to increase the competitiveness of FCVs sufficient to allow them to capture a significant market share. It must be remembered that continuing reductions in FCV costs are expected as a result of additional direct experience, which may mean greater uptake of FCVs in the very long term.

Even though FCVs play a minor role in this scenario, Figure 4-3 shows that a significant although small amount of H_2 is being produced, almost entirely from the gasification of coal. This quantity of H_2 is equivalent to about 3 percent of non-electric final demand by 2100, but if used for car transport would be more than sufficient to supply a global PMV fleet comprising almost 40 percent H_2 FCVs. However, as previously mentioned, H_2 is a convenient and flexible energy carrier and may be sought after for many applications across many sectors, particularly if the cost of other fuels increases as cheaper resource categories (see Rogner 1997) are exhausted.

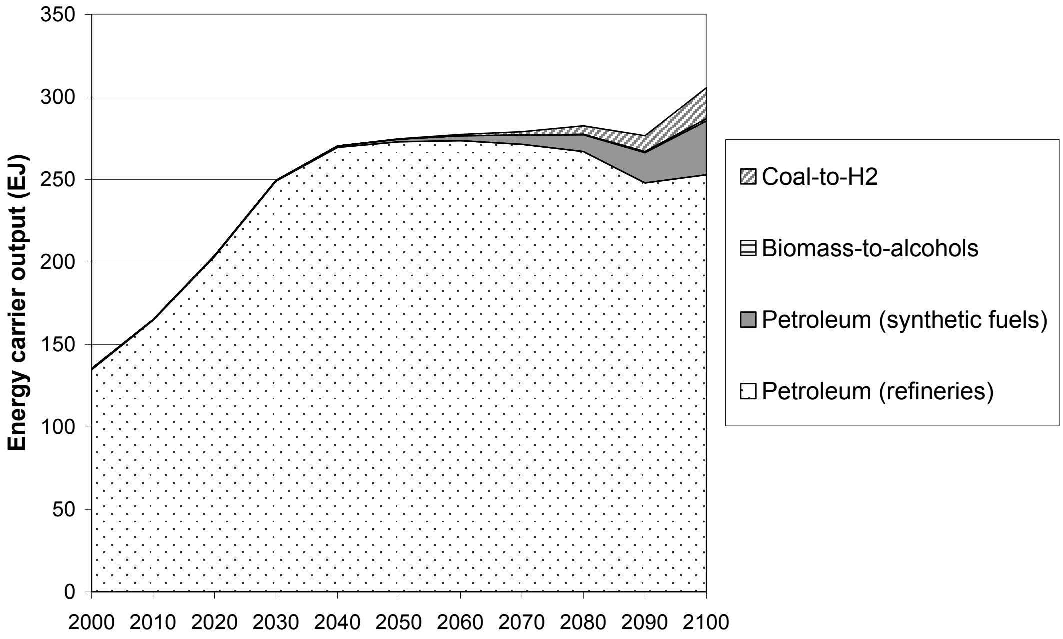

Figure 4-3 Global energy carrier production (secondary energy), with learning in transport technologies, 2000-2100

In the scenarios presented here, it appears that it may be more efficient to use H_2 in non-car transportation—road and sea freight, and air transport—where there are fewer effective fuel and technology substitutes. In the case of air transportation where it is assumed that all demand must by supplied by petroleum products up until 2050, H_2 captures around 13.7 percent of the market by 2100. In the freight transportation market H_2 achieves a lower penetration (less than 1 percent), although this represents a significantly larger amount of fuel than is used in PMV transportation.

The penetration of H_2 in these sectors is not inconsistent with the level of uptake observed in the automobile sector, because these other sectors exhibit a much higher rate of vehicle utilisation which tends to increase running costs relative to capital costs, making the improvements in efficiency afforded by hydrogen (when used in fuel cells) more valuable. In addition, these sectors are better suited to a more centralised refueling network, which is expected to evolve prior to the highly diffuse network required before H_2 becomes convenient for the passenger car market. Lastly, in freight transportation there is more space for on-board H_2 storage and hence cheaper storage options. However, these results must be viewed with caution because of the relatively stylised characterisation in the ERIS model of the air and freight sectors (see Section 3.3.3.4 in Chapter 3).

A large amount of the H_2 produced in this scenario (around 31 percent) is used in the stationary energy sector to supply non-electric energy needs. Stationary use of H_2 to provide for non-electric energy demand avoids many of the drawbacks of using H_2 as a transport fuel. For a start, combustion-based technologies are far cheaper than FCs, and the need for costly and bulky storage is also avoided. In some stationary applications, particularly in the industrial sector where demands are concentrated in a small number of locations, transmission and distribution costs may also be lower.

Hydrogen is attractive in the stationary sector compared to other fuels because of its versatility (compared to direct use of coal or biomass) and the increasing scarcity of oil and natural gas over the century, based on resource availability and demand growth assumptions used here.

A very small amount of H_2 is also used in electricity generation, although in this case there are many cheaper substitutes for oil and natural gas and the contribution of H_2 is insignificant. Direct gas FCs (which produce their own H_2 as an intermediate product, along with surplus heat) make up a larger share of electricity generation, although still account for less than 3.5 percent of total generation in 2100.

4.2.2 Climate change mitigation policies

The scenario presented in the previous section was constructed on the basis that the economic costs of alternative future energy and transportation technology options represent a good proxy for social costs. That is, the ERIS energy system model was applied so as to minimise total economic costs (discounted energy system costs, in this case) when selecting the suite of technologies that will meet future transportation and other energy demands.

However, there is a strong argument that the social costs of various technology choices are greater than the simple economic costs and a proper accounting of non-market costs could lead to a different choice of technologies (see for example Ogden *et al*. 2004). This is particularly relevant in the context of realising sustainable development, where evidence to date suggests that optimising outcomes based on current market organisation (and imperfections) alone may be more likely to threaten, rather than contribute to sustainability.

To address the potential role of the transport sector in a more sustainable global energy system, in this section we examine one of the most significant non-market cost imposed by the energy system: climate change. Importantly, we have excluded other important factors such as local and regional air pollution and security of supply in order to focus solely on the climate change mitigation potential of transport technologies (although there may be synergies between climate change and security of supply—an issue examined further in Chapter 5 and Turton and Barreto (2006)). Although estimating the social cost of anthropogenic greenhouse gas emissions is beyond the scope of this chapter, we have examined how GHG abatement policies may affect the choice of car transportation technologies by way of imposing various levels of carbon-equivalent (C-e) taxation. The use of a C-e tax allows non-CO_2 abatement opportunities to compete with energy system abatement, forest sinks and carbon capture and storage (CCS).

Figure 4-4 shows the impact of global emissions taxes ranging from \$0-1000/tonne C-e on the uptake of FCVs, based on the assumptions used in this analysis. Figure 4-4 presents for each tax rate the share of passenger car travel supplied by FCVs and the quantity of H_2 produced globally at the end of the century. The level of H_2 production is reported to illustrate the relationship between this fuel and FCV uptake, and the effectiveness of abatement policies in promoting the use of H_2. The impact of the C-e tax on atmospheric CO_2 concentrations in 2100, as calculated using the simple climate model MAGICC (see Chapter 3; Hulme *et al.* 2000; Wigley and Raper 1997; Wigley 2003) is also presented in Figure 4-4.[33] The \$0/tC-e case, where FCVs capture roughly 0.5 percent of the market by 2100, is the same as discussed

[33] Using mid-range estimates for climate sensitivity, 1980s-mean net deforestation and aerosol forcing parameters, and defaults for other parameters.

in Section 4.2 and presented in Figure 4-2 and Figure 4-3. This scenario results in an atmospheric CO_2 concentration of 850 ppmv in 2100, with emissions from all sources peaking at 29.6 Gt C-e in 2080.[34]

The plot of FCV share and H_2 production in Figure 4-4 can be divided into roughly three regions based on changing responses to the emissions tax. By contrast, increasing GHG tax rates have a far more consistent impact on atmospheric CO_2 concentrations.

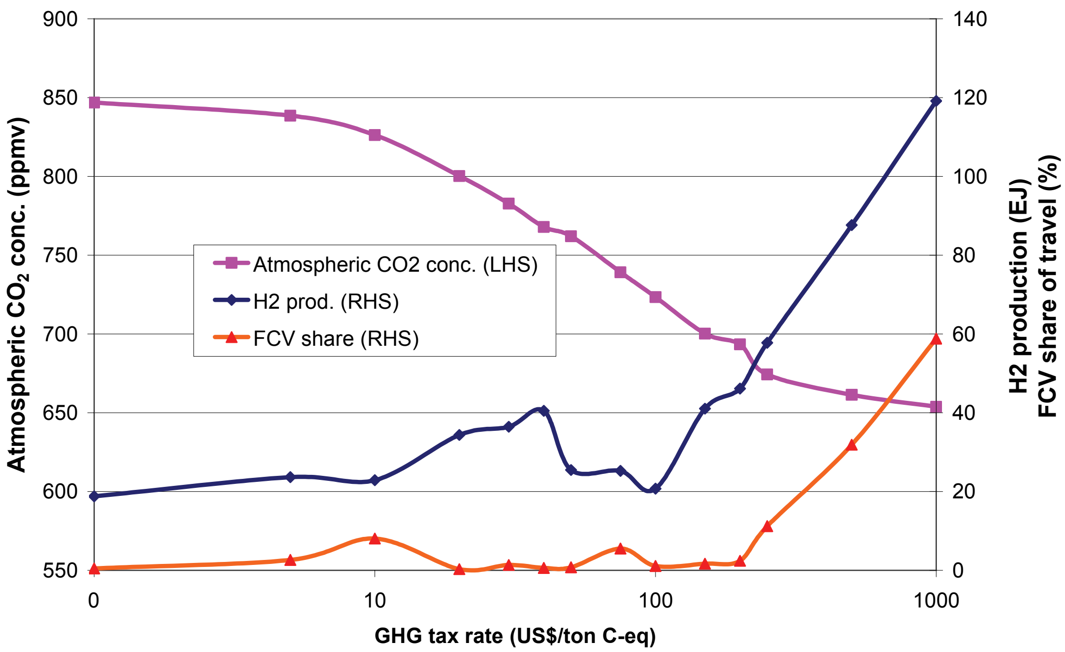

Figure 4-4 Impact of greenhouse gas tax on FCV uptake, H_2 production and CO_2 concentration, 2100

The first region in Figure 4-4 covers low GHG tax rates ($5-40/t C-e) which appear to provide a low and inconsistent incentive for the uptake of FCVs, although these rates are generally supportive of increased H_2 production by the end of the century, particularly from coal. Coal-to-H_2 production technology is an effective means to improve the efficiency of coal utilisation (since H_2 can be used more efficiently and flexibly than coal), thereby reducing emissions. In the scenario examined here, the H_2 is not consumed to any great extent in PMV transportation, for many of the reasons discussed previously in Section 4.2.1. In other words, although supportive of H_2 production low GHG taxes do not appear to significantly advantage FCV technologies relative to ICEV and HEV technologies.

At intermediate C-e tax rates ($50-150/t C-e) FCVs are still unattractive, with these tax levels tending to favour HEVs. Figure 4-5 presents the share of each technology at a $150/t C-e tax as an illustrative case. Compared to the zero C-e tax case presented in Figure 4-2, this level of tax fails to induce substantial additional uptake of FCVs. However, the GHG constraint clearly affects the uptake of the HEVs, bringing forward the timing of HEV market

[34] It should be noted that these differ from the emissions and concentrations for the SRES B2 scenario (Riahi and Roehrl 2000; Nakicenovic and Swart 2000), upon which some of the inputs to the analysis were based (see Chapter 3). As noted in Section 3.2.1 of Chapter 3, it is not the intention to reproduce the SRES B2 scenario here.

dominance (i.e., more than 50 percent of travel) from 2060-70 to 2040-50. The GHG constraint also has a positive impact on the use of natural gas and alcohol fuels in PMV transportation in this scenario. The share of travel by gas-fueled vehicles peaks above 60 percent in 2070, compared with 45 percent in the unconstrained case, while alcohol-fueled vehicles account for 20 percent of travel at the end of the 21st century, compared with 1 percent in the baseline scenario.

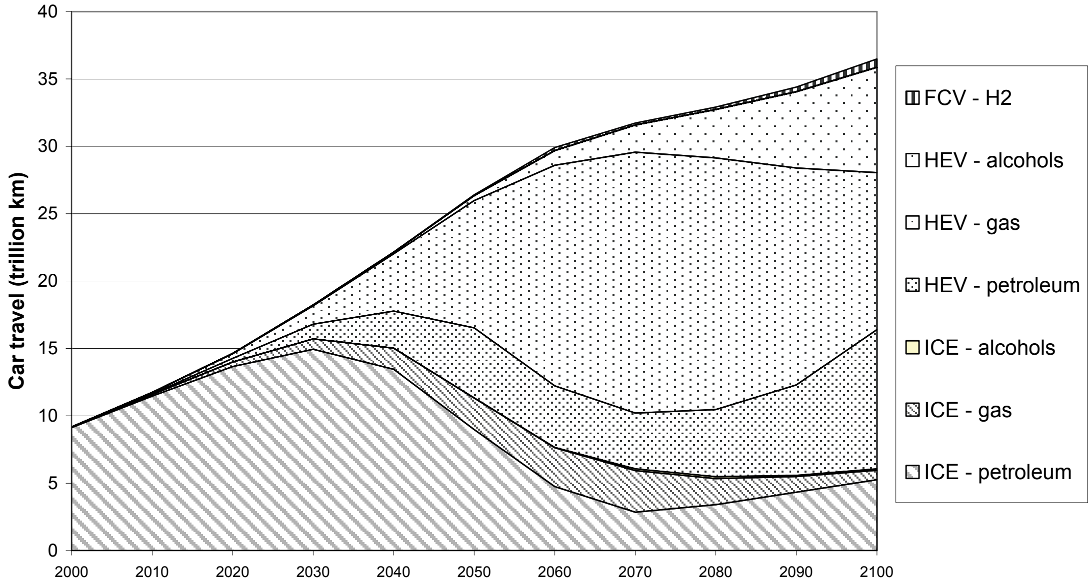

Figure 4-5 Global car travel by drivetrain technology and fuel under a $150/t C-e tax (with learning-by-doing in mobile FC, reformer and battery system), 2000-2100

Abbreviations are as follows: ICE—conventional internal combustion engine vehicle; HEV—hybrid ICE-electric vehicle; and FCV—hybrid fuel cell-electric vehicle.

Across this intermediate range of tax rates the pattern of H_2 production and use is influenced by a number of different factors, and initially decreases to around the level observed in the absence of a carbon tax before more than doubling. The decline shown in Figure 4-4 at around $50/tC-e occurs because at these tax rates the emissions intensity of coal feedstock used for H_2 production begins to outweigh the efficiency benefits of H_2. Production from coal in 2100 under this tax rate ($50/tC-e) is around 45 percent lower than in the $40/tC-e tax scenario. Further, carbon capture and storage (CCS) is not, for the most part, a competitive abatement option at these tax rates.[35] Hydrogen production remains low between $50 and $100/tC-e, although the relative competitiveness of biomass-to-H_2 improves substantially across this range—around 80 percent of H_2 comes from coal at $50/tC-e, whereas at $100/tC-e 80 percent is produced from biomass. At $100/tC-e CCS from H_2 production also starts to become attractive, and provides an additional source of abatement. However, in the scenarios examined here it is assumed that there is a constraint on the availability of CCS from H_2 production, reflecting the limited suitability of some H_2 production sites for CCS.[36] Between

[35] This is despite that fact that carbon capture technologies, both amine- and SOLEXOL-based, benefit from learning-by-doing in the carbon absorption component. However, even though a high learning rate is assumed (15 percent), it is also assumed that the floor cost of this component is high.

[36] Namely, sites that are either too small or dispersed to connect to a CO_2 pipeline network, or too distant from possible storage locations.

\$100 and \$150/tC-e H_2 production doubles mostly as a result of increasing biomass-to-H_2 production, and coincides with full exploitation of CCS opportunities from H_2 production.

Interestingly though, at the higher end of this range of GHG tax rates the additional H_2 production does not coincide with any significant increase in the use of FCVs, implying that under the assumptions in the ERIS model it may be more cost-effective to use the H_2 in other sectors, for many of the same reasons discussed in the baseline scenario (Section 4.2.1). However, H_2 becomes less attractive as a fuel for stationary combustion as the GHG tax is increased from \$50 to \$100/tC-e, with the proportion of hydrogen used to supply stationary thermal needs dropping from around 60 percent to 10 percent across this tax range. This occurs because higher tax rates tend to favour more efficient use of H_2 in electricity generation and freight transport.

The third region in Figure 4-4 covers the high GHG tax rates (\$200/tC-e plus), which under the assumptions modelled here are necessary to provide a consistent and increasing incentive for the uptake of FCVs (see, for example, Ogden *et al.* 2004). Only at these high tax rates do the efficiency benefits of FCV technologies begin to outweigh the cost barriers, which at lower tax rates tend to favour H_2 use in lower-efficiency applications. In fact, H_2 use in direct stationary combustion is largely unchanged between tax rates of \$100/tC-e and \$250/tC-e despite the large increase in total H_2 production, while the H_2 FCV share of PMV travel increases from less than 1 to more than 10 percent. This displaces petroleum use in transportation, and the overall increased energy efficiency (owing to the use of FCVs) allows final demands to be met with less total primary fuel. At \$500/tC-e and above FCVs are highly competitive because of their efficiency and ability to utilise (via H_2) biomass, a carbon-free and reasonably abundant primary feedstock. However, at these taxation levels flexible zero- and low-emissions fuels such as H_2 are competitive across many sectors.

This increasing competitiveness of H_2 at these high GHG tax rates is reflected in Figure 4-4, where H_2 production increases across this range of taxes. Biomass-to-H_2 remains the preferred source of production, although at around \$150/tC-e all suitable sites for CCS from H_2 production are fully exploited under this scenario, slowing H_2 uptake between \$150 and \$200/tC-e. As mentioned above, at tax rates above this level H_2 is a highly sought after fuel and uptake is rapid.

As a brief aside, it should be noted that high GHG tax rates result in significant electricity generation from stationary H_2 FCs by 2100 (4.3 percent of total generation at a C-e tax of \$250/tC-e, using almost half of the total H_2 produced). As with FCVs, this generation is attractive because under stringent abatement policies the high efficiency of fuel cells outweighs their higher cost compared to other technologies. In addition, the fact that at high GHG tax rates H_2 is used to produce electricity implies that even if the modelling assumptions were relaxed to allow for production of H_2 using electrolysis, this production route would remain unused (see Section 3.3.4.1 in Chapter 3).[37]

The above results imply that the application of broad abatement instruments (such as a carbon tax, or emissions trading) alone is insufficient to bring about a consistent transition to FCVs, except at very high levels (for a discussion see, for example, Keith and Farrell 2003). Nor is promoting the use of FCVs in passenger car transportation necessarily a cost effective way to

[37] For the analysis presented in Chapter 7, electrolysis is included as a hydrogen-production technology. Nonetheless, the results in Chapter 7 tend to confirm the findings presented here.

abate greenhouse gas emissions, except where deep cuts in emissions are required or over the very long term.

4.2.3 Infrastructure policy

Policy-makers may wish, however, to promote FCVs in the medium-to-long term for reasons other than climate change mitigation, such as reducing local and regional air pollution, diversifying the transportation fuel mix to improve security of supply, or to secure first-mover advantage in the application and development of advanced transportation technologies. That is, where other non-market benefits (and other aspects of long-term sustainable development) are worthwhile pursuing despite the high abatement costs associated with the deployment of FCVs.

Since broad-based abatement instruments appear to be an ineffective and costly way to bring about an increase in the number of FCVs, it seems sensible to examine policies that are more FC-specific to see whether they are a more effective alternative. Accordingly, this section examines the impact of a policy where, in addition to a C-e tax, public support is provide for the development of a H_2 transmission and distribution infrastructure system. Specifically, part of the capital cost of developing a transmission and distribution network is assumed to be subsidised.

The need to develop expensive transmission and distribution infrastructure to make H_2 available and convenient is often cited as one of the major barriers to the widespread utilisation of H_2 in transportation (Barreto *et al*. 2003). The distribution network must be developed initially in the absence of any broad demand for H_2, and the model used here attempts to incorporate the costs of this and other transport fuel transmission and distribution infrastructure, including the need to develop a minimum network irrespective of the quantity of fuel delivered (see Section 3.3.4.2 in Chapter 3).[38]

This representation of transmission and distribution network development enables us to investigate how significant a barrier infrastructure costs are to the uptake of advanced transportation technologies, given that the vehicle costs alone may make these technologies uncompetitive (see Box 3-2 in Chapter 3). This may be particularly useful for policymakers interested in the effectiveness of different approaches to promoting H_2 as a transport fuel.

Accordingly, a scenario was examined in which the capital cost premium of H_2 transmission and distribution infrastructure over that of petroleum is funded externally—for example, by a government pipeline and reticulation subsidy program. The impact of such a program on the overall cost of H_2 FCVs is small, with transmission and distribution capital costs accounting for only roughly 3 percent of the per kilometre cost of the H_2 FCV drivetrain and fuel costs. However, these capital costs account for 50 percent of the premium over the nearest cheaper competitor (alcohol hybrids) for North America based on initial resource costs (again, refer to Box 3-2 in Chapter 3).

The results of the analysis of this infrastructure subsidy scenario with ERIS show that the subsidy policy raises the share of FCVs in 2100 from roughly zero to 8 percent. However, because of the inconsistent response observed at low GHG tax rates in Section 4.3 this result cannot be viewed as significant. This is illustrated in Figure 4-6, which compares the impact

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[38] This was modelled using an binary decision variable to reflect the use of hydrogen, coupled with a minimum capacity requirement of 40 GW (or 20 GWy of H_2 distributed) per region.

of the GHG tax with and without the support for H_2 T&D infrastructure. Figure 4-6 shows that supporting H_2 T&D infrastructure does not have a major impact on the uptake of FCVs across a range of C-e tax rates. However, it should be noted that supporting H_2 T&D does have a generally positive impact on H_2 consumption, which is on average 40 percent higher under the infrastructure policy across the C-e tax rates examined (not shown).

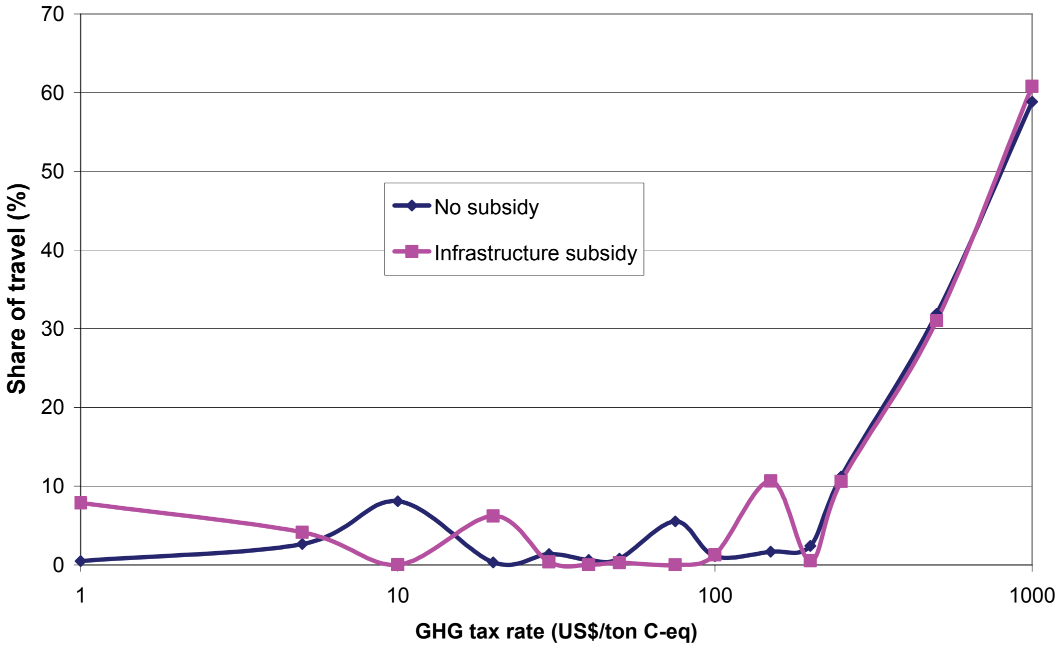

Figure 4-6 Impact on share of FCVs of infrastructure policy at different GHG tax rates, 2100

These results imply that if the policy goal is to promote FCVs, then some other highly specific policy instrument is required. Many possibilities exist, including targets or standards for vehicle manufacturers or distributors, government procurement programs, direct financial incentives through tax credit schemes or feebates regimes, and ease-of-use-enhancing policies such as granting permission to access high-occupancy vehicle lanes or providing free parking to FCVs. However, the results of the analysis in Sections 4.2 and 4.3 imply that FC-specific policies are very unlikely in themselves to represent cost-effective ways of pursuing climate change mitigation or promoting development of a H_2 economy. For this reason, the potential impact of the diverse array of highly specific FC policies is not examined further in this chapter.

4.3 Discussion and conclusions

4.3.1 Transport demand

There are a number of important insights arising from the analysis presented in this chapter, of particular relevance to the possible emergence of a sustainable transport sector, and the potential contribution of transport to sustainable development. In addition, this analysis has illustrated some of the features and an application of the modelling framework described in Chapter 3.

Before we discuss in detail some of the implications of the results presented above, it is important to first be emphasise that the transport demand scenario used in this analysis is based very much on business-as-usual growth with a continuation and, in developing regions, repeat of historical trends experienced in developed regions (see Section 3.2.2). However, whether these trends will continue is uncertain and, for example, the time-money budget relationship upon which this scenario is based (see Schafer and Victor 2000) may break down above a certain travel threshold, perhaps as a consequence of increasing congestion, loss of amenity, and local/regional air pollution. This may be more likely if one considers the possibility that, at high levels, income becomes a poor proxy for well-being—that is, where the marginal impact on well-being of additional disposable income is small compared to the marginal negative impact of additional congestion or pollution.

In addition, the scenario does not anticipate a shift to more sustainable transportation modes, a redesign of urban areas, or any possibility of an information and communications technology-driven reduction in the need for travel (as mentioned in Section 3.2.2). Rather, it is a "what if" scenario that explores the implications for new transportation technologies of a continuation of current trends in passenger transport, many of which appear unlikely to change in the medium term. This scenario is useful in the context of examining the energy system changes necessary to achieve deep cuts in GHG emissions when demand is inflexible.[39]

For instance, at the highest GHG tax rate examined ($1000/t C-e) FCVs account for around 60 percent of global PMV transportation at the end of the 21st century. However, in the scenario examined here, even at this tax rate atmospheric CO_2 concentrations still exceed double pre-industrial levels by 2100 (IPCC 2001). This highlights the need for substantial additional and expensive changes throughout the energy system, including in transport to achieve deeps cuts in emissions (this is examined in more detail in Chapter 6 and Chapter 7, where achieving more stringent climate change targets is investigated). In the case of car transportation this may imply that a major technological shift in transportation is insufficient, and hence demand reductions and modal shift may also be necessary. Such changes would reduce the need for severe and rapid action in other sectors, and reduce the stringency of any GHG tax (or similar instrument) required to achieve a given abatement target. This highlights the potential importance of PMV travel demand reductions in meeting stringent GHG abatement targets, particularly since the absence of demand-side action in transport implies additional costly action in other wealth- and employment-creating sectors. However, restricting personal mobility may undermine other elements of development and human welfare. Accordingly, in subsequent analysis, particularly in Chapter 7, this dissertation continues to explore the implications for climate change (and other aspects of sustainability) of a more-or-less unrestricted mobility scenario. This approach has additional advantages in that it can provide policy insights illustrating the potential trade-offs between energy system transformations and restrictions on mobility, compared to the alternative of simply assuming that mobility can be restricted.

4.3.2 Technological learning

The technology cluster approach employed in the analysis presented here helps to provide a relatively realistic characterisation of the interaction between different technologies. In the case of vehicle technologies, it plays an important role in increasing the relative

[39] It should be noted that in Chapter 6 the modelling framework from Chapter 3 is extended to incorporate some features to make demand more flexible to price. However, the potential willingness to forego travel for other reasons is not explored.

competitiveness of FCVs as a consequence of experience with the HEV battery system and stationary FC. However, even with the benefits of these technology spillovers, in the absence of additional supporting measures FCVs are likely to struggle to gain a significant market share.

On the other hand, assuming that car transportation technologies do not benefit from experience leads to the unsurprising result that new and very expensive technologies (which remain expensive regardless of experience) are not used. Only with extremely high resource costs is this likely to change.

Learning in car technologies and fuel production has a significant impact on technology uptake. Since FC technologies are still in their infancy, it can be reasonably expected that they have a promising learning potential in the long term. However, it should be noted that the least-cost optimisation approach used in this and almost all similar studies accepts that energy and transport market participants possess perfect foresight. In the case of learning, this assumption implies that participants are aware of the rate and extent of any benefits gained from experience using a new technology, and so make optimal and early investments. However, in many cases new technologies are risky and first-movers may face higher costs, which tends to delay the uptake of technologies (Rogers 1983). This market failure necessitates policy intervention to promote sufficient technology utilisation to achieve the optimal learning potential and hence least cost (see, for example, Ogden *et al.* 2004). One possible way to effectively stimulate the learning process is to establish international public-private partnerships to share costs and risks of R&D, demonstration and deployment programs (RD3) (for example, see PCAST 1999). Other policy interventions could include "buy-down" strategies, infrastructure development, other R&D support and pollution taxes. However, we have seen that GHG taxes may not be effective in promoting FCV uptake, even when there is perfect foresight.

4.3.3 Barriers to the use of hydrogen in car transportation

One of the advantages of using an energy-system model to examine the development of the car transportation market is that it incorporates likely competing demands for fuels. As briefly mentioned earlier, H_2 is a highly flexible energy carrier and it can be expected that many sectors will demand H_2 in the long run if this fuel can be produced and delivered competitively. The extensive possibilities for hydrogen use are particularly relevant when considering that substantial barriers must be surmounted before the use of H_2 in passenger car transportation can become widespread. These barriers include the high capital cost of FC and on-board storage systems, and the cost of distributing H_2 to many small refueling sites. By contrast, barriers to the use of H_2 in some other sectors, including some other transportation sectors, appear less daunting.

For example, stationary applications avoid most of the storage costs associated with the use of H_2, although very-small scale applications (such as in the residential sector) may entail additional distribution costs. Storage costs are also relatively smaller for transport modes relying on large vehicles (ships, trucks, buses), and the use of H_2 in transport modes with higher utilisation rates (ships, planes, trucks, buses, taxis) overcomes some of the capital cost constraints experienced by private passenger cars. Further, applications relying on H_2 combustion rather than FCs—such as jet engines or supplying thermal requirements—also avoid high capital costs, while using H_2 in sectors where demand is highly concentrated at a few sites (such as heavy manufacturing) avoids some of the costs of establishing a large-scale transmission and distribution network.

Accordingly, it may be more efficient to use H_2 for applications other than car transportation and, despite the stylised representation of some sectors in the ERIS model, the scenarios examined here appear to support this conclusion. It should be noted that the additional expense and lower efficiency of the direct alcohol and petroleum FCVs, render them relatively unattractive even though they avoid the need for costly transmission and distribution infrastructure.

On the other hand, if the policy goal is to support the FCV market then it is important to be aware that market interventions that address only one barrier to the uptake of FCVs (particularly if that is a barrier shared by other sectors competing for H_2) are unlikely to be sufficient, pointing to the need for a coordinated market strategy (for example, see NHA 2000), possibly combined with highly specific policy intervention.

4.3.4 GHG mitigation policies

GHG mitigation policies, applied in the scenarios examined here as a comprehensive GHG tax, have an inconsistent impact on the uptake of FCVs in car transportation. Only high GHG tax rates ($250/t C-e and above) provide an adequate and consistent incentive to FCVs. From a policy perspective this indicates that promoting FCVs is not a cost-effective way of reducing GHG emissions except in the long term or where stringent cuts in emissions are required. In other words there are many cheaper alternative abatement options across all sectors, including in PMV transportation where the use of HEVs and a shift to gas or alcohol is preferable from the point of view of cost-effectiveness. It should be noted that this discussion relates almost entirely to H_2 FCVs, since the direct alcohol and petroleum FCVs are uncompetitive at all but the highest GHG tax levels. Moreover, it should be emphasised that the preliminary analysis presented in this chapter examines only one element of long-term sustainable development, and FCVs may potentially have a place in a more comprehensive sustainability strategy. This is explored further in the following chapters.

Low levels of GHG taxation generally promote H_2 production from a small base, although above a certain threshold ($50/tC-e in the scenario studied here) coal-to-H_2 production is more costly, and the widespread use of either biomass feedstocks or carbon capture technology is only cost-effective at higher GHG tax rates. Most of the H_2 produced at low to intermediate tax rates is used in applications where there are fewer barriers to H_2 uptake, rather than in FCVs. At much higher tax rates, the increasing competitiveness of FCVs "frees up" other transport fuels, particularly petroleum, that can be used elsewhere.

4.3.5 Hedging climate change risks with hydrogen

One of the benefits of developing a H_2 distribution infrastructure system, thereby overcoming one of the major barriers to greater use of H_2, including in FCVs, is that it makes available additional cost-effective abatement options. Thus, pursuing demonstration and deployment of hydrogen production and end-use technologies may constitute a "hedging" strategy against the risks of uncertainty in climate change, particularly the possible need to pursue deep cuts in emissions.

The additional abatement opportunities arise because of the characteristics of H_2 production, namely: it can be produced from a variety of feedstocks, including natural gas, coal, biomass, electricity, uranium and solar energy (the latter two by exploiting direct thermochemical reactions); and, its production from primary fuels can be combined with CCS technologies such that it becomes a low- or negative- carbon (in the case of biomass) fuel. Moreover, it is potentially a highly flexible and convenient energy carrier, unlike some of the feedstocks from which it can be produced—particularly coal and biomass. That is, the use of H_2 increases primary fuel flexibility and facilitates deeper cuts in emissions. Importantly, this primary fuel flexibility also means that hydrogen may be an attractive fuel in world regions confronted with uncertainties associated with future fuel resource availability and cost—both geological and geopolitical (see Turton and Barreto 2006).

Although subsidising the capital costs of H_2 transmission and distribution infrastructure does not necessarily lead to increased uptake of FCVs, it does result in additional H_2 production, and the development of a more extensive T&D network which reduces the additional cost of switching to technologies such as FCVs. That is, support for H_2 T&D may be one element in a coordinated market strategy for the eventual introduction of FCVs. It also results in broad abatement instruments becoming more effective at promoting H_2 and H_2-using technologies.

4.4 Final comments

It is important to stress that our results and findings depend on the modelling assumptions outlined in this and the previous chapter, about which there are a number of uncertainties. In particular, technological uncertainty is potentially significant and the possibility of technology breakthroughs cannot be ruled out. Specifically, faster technological development that leads to a rapid decrease in the costs of FCs may accelerate the uptake of FCVs and allow them to capture a larger share of the transportation market.

Furthermore, we have examined only one of the main social and policy drivers of the development of the global energy system—climate change. The potential impact of pursuing other social goals related to transport, such as reducing local air pollution or maintaining security of energy supply, may alter the development of the energy system and promote the adoption of technologies that are not necessarily the most cost-effective options for climate change mitigation. However, there could also be synergies between technology choices for GHG mitigation and those necessary to comply with policies to curb air pollution or enhance security of energy supply. The following chapter explores this in more detail, although across a wider range of technologies and energy sectors.

One final point to consider from this analysis is that for all the advantages of least-cost optimisation modelling employed here, it is important to consider the extent to which consumer behaviour and choice of technology is driven by minimisation of costs. For example, after accounting for technology learning the difference in cost per kilometre between the H_2 FCV and the cheapest technology assumed in this analysis is around 1.25 cents (see Box 3-2 in Chapter 3), which is sufficient to severely restrict the market share of H_2 FCV over this century under the baseline scenario. However, this difference in cost is roughly the same as the additional cost of using an ICEV that consumes 11 l/100km compared to one that consumes 8 l/100km.[40] Current experience in the passenger transportation sector in some developed regions shows that consumers often prefer the more costly vehicle, a response which least-cost models are unable to capture. This implies that there may be policy

[40] Based on the USA with a price of US$0.45 per liter gasoline (IEA 2003c).

interventions other than abatement instruments or technology-specific programs that do not necessarily promote least-economic-cost outcomes but rather exploit malleable consumer preferences in socially beneficial ways. This needs to be considered by policy-makers and modellers when interpreting estimates of the cost and competitiveness of technologies and abatement options, and in developing policies.

Chapter 5. Elements of a sustainable energy system: security of supply and climate change mitigation

5.1 Introduction

Security of energy supply has recently re-emerged as a focus of government policy intervention throughout much of the world. Geopolitical developments in a number of world regions have driven much of this renewed interest, although the impact of supply shortages caused by domestic market, institutional and regulatory failures (most notably in California in 2000) have provided additional impetus to the renewed concern. The current overall dependence of OECD countries on oil supplied from politically volatile regions and the definition of appropriate responses to potential supply disruptions remain challenging policy issues (e.g. EC 2001; IEA 2001b; DOC 1999).

These concerns have arisen in a world where energy demand is expected to grow rapidly over the next century, notwithstanding some decoupling of energy consumption from economic activity (Odell 2004; IEA 2004; EIA 2004). This will place additional demands on global energy resources, and expose an increasing number of countries and people, and proportion of global economic activity, to potential threats to supply security. This will be compounded by depletion and eventually exhaustion of global oil and gas resources,[41] although this in itself will probably manifest as a gradual process rather than an unpredictable supply disruption, since increasing scarcity should improve the commercial viability of less economic reserves, spur additional exploration, promote technological innovation and encourage conservation. However, access to abundant and cheap fuels will be diminished and poor management of the transition away from exhaustible resources could potentially increase vulnerability to other less predictable supply disruptions.

Concerns over the potential conflict between increasing demand and security of supply are complicated further by uncertainty over which fuels and energy carriers will supply future needs. For example, the emergence of a global energy system where hydrogen (H_2) becomes one of main final-energy carriers is receiving increasing attention. A “hydrogen economy” fueled by low-emissions primary energy sources is not only a potential route for achieving sustainability goals in the energy sector (see e.g. Ogden 1999; Barreto *et al.* 2003), but also a potential means by which to diversify the energy supply, and hence reduce security risks associated with some energy sources.

Much of the uncertainty over potential future developments in the evolution of the energy system, such as the possible emergence of a H_2 economy, stems from the always-active, although uncertain in pace and direction, force of technological change. Its cumulative and pervasive effects could transform substantially the technologies and systems upon which the energy system is based (for a discussion, see e.g. Nakićenović 1991). The impact of these effects on supply security is uncertain, partly because threats to security are themselves uncertain and many other factors driving technology evolution may take precedence. However, a sound security of supply concept calls for, among others, a diversification of technologies and energy sources (EC 2001).

Another key factor likely to drive the development of the global energy system in the long term is the need to substantially reduce the emissions of greenhouse gases (GHGs) (IPCC

[41] Although there is some debate about the origins of geological stores of carbon fuels (see summary in Odell 2004, Chapter 6), and the theory of an abiogenic origin implies replenishment of some oil and gas fields.

2001a,b,c). The potential trade-offs and synergies between policies addressing security of supply and climate change mitigation deserve greater attention. In addition, such policies also have implications for resource sustainability and technology development. For example, many have recognised the potential for energy efficiency and renewable energy technologies to assist in achieving security of supply outcomes, while simultaneously promoting sustainability goals (EC 2001, Abraham 2001). How these trade-offs and synergies play out will depend on the circumstances of, and strategies employed by countries—for instance, regional security-of-supply considerations may introduce a so-called "how" inefficiency in the mitigation of GHGs (see Brown and Huntington 2003; Huntington and Brown 2004). Specifically, a country or region may follow a strategy to selectively reduce consumption of imported fuels, thereby reducing vulnerability to supply disruptions, even though such strategy may not necessarily coincide with the least-cost GHG abatement strategy for the world as a whole (Brown and Huntington 2003).

The study described in this chapter seeks to examine the interactions and synergies between climate change mitigation and supply security risk management policies, and to investigate the role of technology in achieving these policy goals. For this analysis we use ERIS (Energy Research and Investment Strategies), the "bottom-up" energy-systems optimisation model described in Chapter 3. ERIS represents key technologies and technology dynamics, specifically endogenising technology learning patterns, and permits the examination of security of supply within the context of the global energy system with competing demands for, and sources of, fuels.

The remainder of this chapter is organised as follows. Section 5.2 presents a brief description of the characteristics of the modelling framework presented in Chapter 3 most relevant for assessing security of supply, including the assumed resource supply and technology characteristics. Section 5.3 describes construction of appropriate policy scenarios to study synergies and side-benefits of pursuing security of supply and climate change mitigation. Section 5.4 describes the results of the analysis, and is divided into a number of sub-sections. Section 5.4.1 presents a baseline scenario that illustrates how business-as-usual technology and energy system development affect supply security over the long term, while the impact of targeted security of supply and climate change policies is considered in Section 5.4.2. The impact of supplementing these policies with technology deployment policies is considered in Section 5.4.3. Finally, Sections 5.5 and 5.6 outline some conclusions and policy insights.

5.2 The energy-systems ERIS model

The ERIS (Energy Research and Investment Strategies) modelling framework applied in this analysis is described in more detail in Chapter 3. However, it is perhaps helpful to remind the reader of the specific technologies in ERIS that may be relevant for security of energy supply, particularly those technologies with the potential to reduce regional dependence on the scarcer and less evenly distributed sources of energy—notably oil and gas. The ERIS model incorporates the following energy-carrier production technologies that are capable of utilising more abundant but less flexible primary fuels to produce flexible energy carriers:

- electricity generation technologies such as:
  - coal-based, nuclear, solar, wind, hydro, biomass, H_2 fuel cells;
- liquid and gaseous fuel production technologies that utilise coal and biomass, comprising:
  - synthetic fuel (Fischer-Tropsch (FT)) production (coal);

- H_2 production (coal, biomass); and
- alcohol production (biomass).

In addition, a number of technologies that improve the efficiency of gas and oil utilisation are incorporated into ERIS, including:

- stationary gas combined cycle and fuel cell electricity generation; and
- efficient transportation technologies that reduce the total primary energy needs, comprising hybrid-electric and fuel cell vehicles.

5.2.1 Global regions, demands and fuel resources

As discussed in Chapter 3, the ERIS model distinguishes between eleven world regions, following the MESSAGE model's regional structure (Messner and Strubegger 1995). Security of energy supply is examined here in the context of inter-regional fuel flows, and it is assumed that intra-regional fuel flows are not vulnerable to supply disruptions.

Assumptions on the fossil-fuel resource base rely on the estimates of Rogner (1997) and, as discussed in Chapter 3, a relatively large availability of oil and gas is assumed in the ERIS model, and coal and uranium are considered to be globally abundant. The total oil resource assumed to be available in the ERIS model corresponds to roughly 5,500 billion barrels in 2000, which is in line with the more realistic estimates from many other sources (see review by Odell 2004, pp. 45-52). Figure 5-1 presents a regional breakdown of oil resources, classified according to the categories defined by Rogner (1997). To recap, Categories I to III represent conventional reserves and resources, whilst Category IV represents the potential for enhanced recovery of the conventional resources. Category V corresponds to the identified reserves of unconventional recoverable oil and gas, and Category VI corresponds to estimates of unconventional oil and gas resources. It should also be remembered that the ERIS model allows for interregional trade of several energy carriers (coal, oil, natural gas and H_2).

For natural gas, this analysis also considers the possibility that 5 percent of the unconventional and additional occurrences (Categories VII and VIII), mainly methane hydrates and geopressured gas, become technically and commercially available (see Table 3-2 in Chapter 3). This is a significant quantity which has the potential to change the development path of the global energy system. Figure 5-2 present the regional breakdown of gas resources (excluding the additional 5 percent of "unconventional and additional occurrences").

To examine how these resources translate into regional supply security, the next section defines some basic concepts. In addition, it discusses the various policy instruments examined in this chapter.

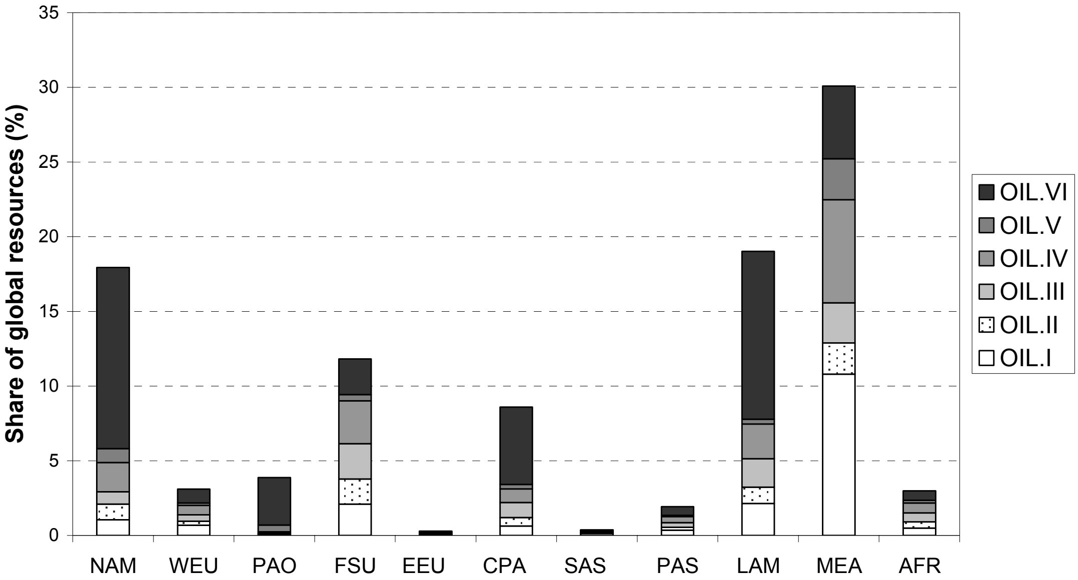

Figure 5-1 Share of global oil resources assumed in ERIS, by region and category

Source: Rogner (1997)

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

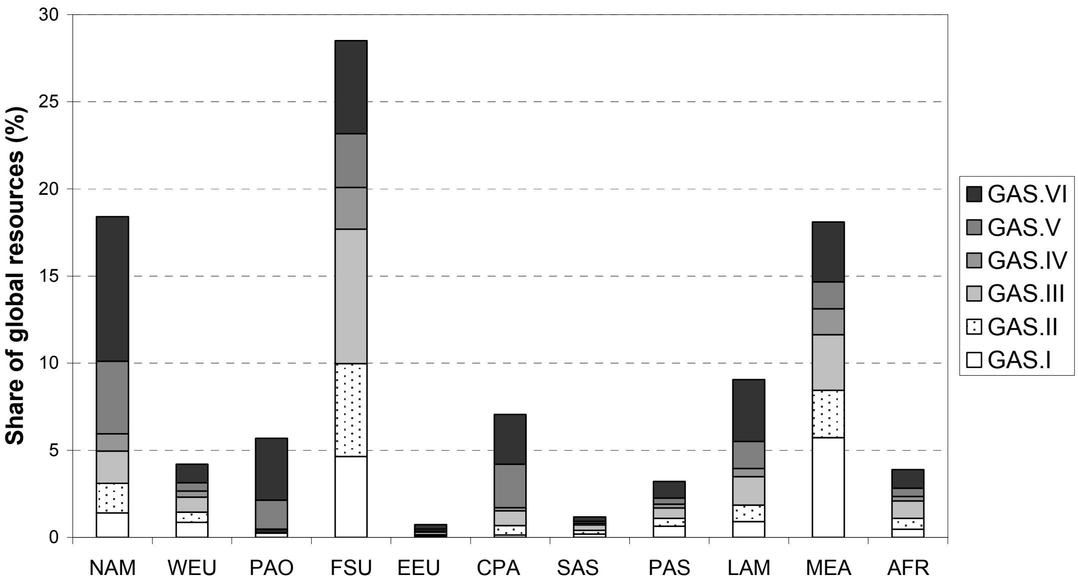

Figure 5-2 Share of global gas resources assumed in ERIS, by region and category

Source: Rogner (1997)

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

5.3 Modelling policy initiatives

At the outset it is worth noting that this chapter does not seek to model the potential costs of an energy supply disruption. Instead, we accept that such shocks are unpredictable and costly, and instead examine the impact of a policy that seeks to reduce the long-term risks associated with supply disruptions, whilst imposing a small and predictable cost. Similarly, this analysis does not seek to examine the potential costs of climate change, only the costs of GHG abatement policies.

It should also be noted that one of the options to improve either supply security or mitigate climate change that is excluded from this analysis is energy or transportation demand reductions. This is not because demand reductions are either ineffective or unattractive as a means to realise long-term sustainable development—quite the contrary—but rather to highlight the implications of trying to achieve security or climate goals without reducing energy demand, and to sharpen the focus by restricting the number of variables in the analysis, enabling us to derive policy insights specific to fuel supply and technologies. The importance of demand reductions in long-term climate change mitigation and supply security is examined in Chapter 6 and Chapter 7.

5.3.1 Modelling security of supply policies

In this analysis it is assumed that a supply security policy is actively pursued by countries in the OECD, Central and Eastern Europe and Centrally Planned Asia (principally China) (see Figure 3-1 in Chapter 3 for a definition of the world regions). These regions are highly import-dependent for oil and gas (see Section 2.1.2), consume the largest amount of these fuels, and are expected to account for a majority of global oil consumption over the long term.

Although there are many possible formulations of energy policies that support long-term security of supply, it is assumed that the effect of all these policies is effectively to maintain a buffer of indigenous resources capable of sustaining regional consumption.[42] Here we assume that these policies manifest as a requirement to maintain:

- a viable regional domestic oil and gas extraction industry capable of rapid expansion to exploit domestic resources if necessary. This is modelled as a requirement until 2050 that vulnerable regions (i.e., those mentioned above) must produce at least 25 percent of their total consumption; and
- regional resources sufficient to supply current levels of regional consumption for a period of at least 20 years, including a requirement to have at the end of the century a buffer for 20 years of projected consumption. Although it seems unlikely that any single supply crisis would last twenty years, a buffer of this size provides more insurance against a series of smaller crises, and provides time to develop and deploy alternative technologies.

This second requirement means that longer-term supply security can be enhanced not only by reducing consumption of oil and gas, but by exploiting the availability of imports in the short-term at times when there are few supply risks.

[42] This assumption relates only to energy policies, and governments have available other ways of influencing the likelihood of supply disruptions in the short term, such as through the use of diplomacy and coercion, which are not examined here.

5.3.2 Modelling climate change policies and combined policies

In this chapter, we examine two different climate change mitigation policies, and how they interact with the security of energy supply policy described above. The first policy is a dynamic cap on global emissions of the three main greenhouse gases (GHGs), which was devised to have roughly the same cost as the security of supply policy. The emissions trajectory under this cap mirrors that produced by the ERIS model under a global $75/t C-e tax. The second policy, the more stringent of the two, is an aggregate cap on emissions designed to result in stabilisation in atmospheric CO_2 concentration at 650 ppmv.[43] We also investigate the impact of the GHG abatement policies, and the security of supply policy, on the technology development pathways followed by the global energy system, and pay specific attention to the role of H_2, a high-quality energy carrier, which has been highlighted as a promising contributor towards a sustainable energy system in the long term (HLG 2003, Barreto *et al.* 2003).

5.3.3 Modelling technology policies that promote supply security or GHG abatement

This chapter also seeks to study the potential for technology policies to lower the cost of achieving security of supply and climate change policy outcomes. Technology policies are modelled in the form of demonstration and deployment (D&D) programmes applied in the base year of the analysis period. Each technology policy is modelled in the form of a deployment 'shock' of $10 billion gross.[44] This shock not only results in installation of an equivalent capacity of the technology, but also increases experience with the technology, resulting in technological learning in the key constituent components. This additional experience may help reduce the costs of the key components, thereby improving the longer-term competitiveness of the 'shocked' technology and others relying on the same components (see Section 3.3.6 for a description of the representation of technologies).

5.4 Results: climate change and energy security

5.4.1 The baseline scenario

One critical factor affecting future supply availability and climate change impact, and hence expected to affect the impact of policies aimed at achieving supply security or climate change outcomes, is the baseline development of the energy system. The extent to which the baseline scenario is oil- and carbon-intensive is expected to have an impact on the cost of maintaining security of supply, or reducing GHG emissions. The baseline scenario employed in this analysis is based on the B2 storyline, although modified to include more detailed representation of the transportation sector as described in Chapter 3.[45] Global demand under this scenario for different primary energy sources is presented in Figure 5-3.

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[43] In comparison, the baseline scenario results in a concentration of roughly 850 ppmv by the end of the century, whilst the mild GHG policy results in a concentration of 750 ppmv (using the MAGICC climate model, see Hulme *et al.* 2000; Wigley and Raper 1997; Wigley 2003). Under both of these scenarios concentrations are still increasing at the end of the century.

[44] That is, the shock covers the entire cost of the technology. In reality, the actual expenditure required from government might only be the difference between the cost of the technology and that of a commercially viable competitor technology.

[45] Some results for the development of the transportation sector under this baseline scenario were presented in the previous chapter.

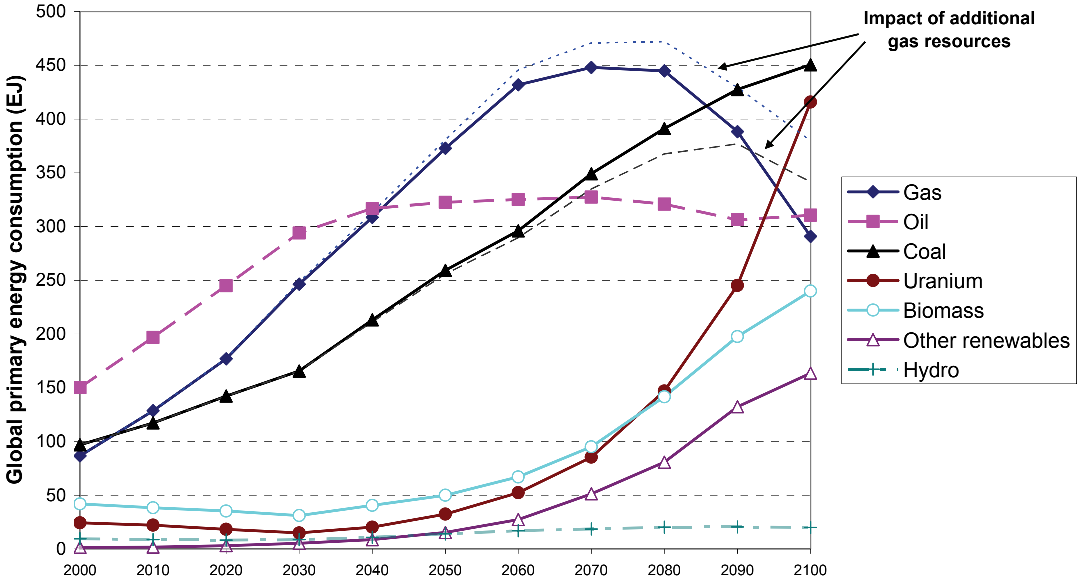

Figure 5-3 Global primary energy consumption, business-as-usual baseline

Under this scenario consumption of all primary energy sources increases to roughly 2070, although global oil production stabilises from around 2040 onwards. Global oil and gas production both peak around 2070-80, after which gas output and consumption drops rapidly. Non-carbon fuel use roughly doubles between 2000 and 2060, and then grows rapidly between 2060 and 2100, led mainly by an expansion of nuclear electricity generation. However, use of renewables other than hydro and biomass increases 100-fold over the century, although these sources still account for less than 9 percent of primary energy[46] at the end of the century. The consequence of these various energy consumption trends is that under this scenario annual global GHG emissions (excluding deforestation) peak at almost 30 Gt carbon-equivalents (C-e) in 2080, and are still at almost three-times 2000 levels by 2100.

Figure 5-3 also shows the impact of assuming that 5 percent of additional occurrences of gas (Categories VII and VIII, mainly methane hydrates and geopressured gas) becomes available, effectively doubling global gas resources (although at a cost assumed to be roughly 50 percent greater than for resource Category VI). This does not significantly change the timing of the production peak for natural gas, although it displaces coal consumption. Apart from a very small reduction in production of other renewables (not shown), the additional gas resources have almost no impact on the other fuels.

In the context of examining the potential for different technologies to help achieve security of supply or climate change goals, it is useful to examine which activities are responsible for the consumption of the fuels presented in Figure 5-3. Accordingly, we show in Figure 5-4 the contribution of different fuels in electricity generation. In the baseline scenario presented here, carbon fuels continue to account for more than half of total electricity generation up until 2090, after which they are increasingly replaced by nuclear generation. Looking at those fuels subject to supply constraints, only gas is predicted to be used significantly in electricity

[46] For non-combusted renewables (excluding hydro) and nuclear energy, primary energy equivalents are calculated based on a conversion efficiency of 38.5 percent. For hydroelectric generation, efficiency is assumed to be 100 percent.

generation, and accounts for over 30 percent of generation over the century, peaking at almost 50 percent around 2030-40.

The other sector of particular interest is transportation, which is currently dependent on oil. Figure 5-5 shows that oil is expected to continue to dominate for the entire century under this baseline scenario, although gas will also account for a large share. Not until the very end of the century is it expected that H_2 will be used in any significant quantities under the assumptions employed in the modelling framework used here. Alcohol fuels remain relatively unattractive throughout the century, with some minor fluctuations in the very low levels of consumption.

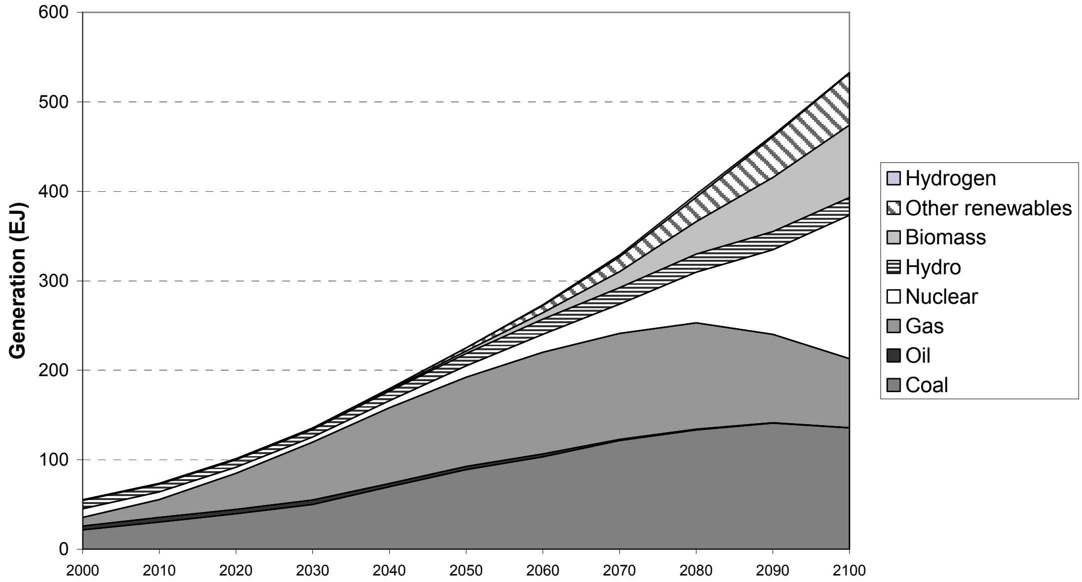

Figure 5-4 Global electricity generation by fuel, business-as-usual baseline

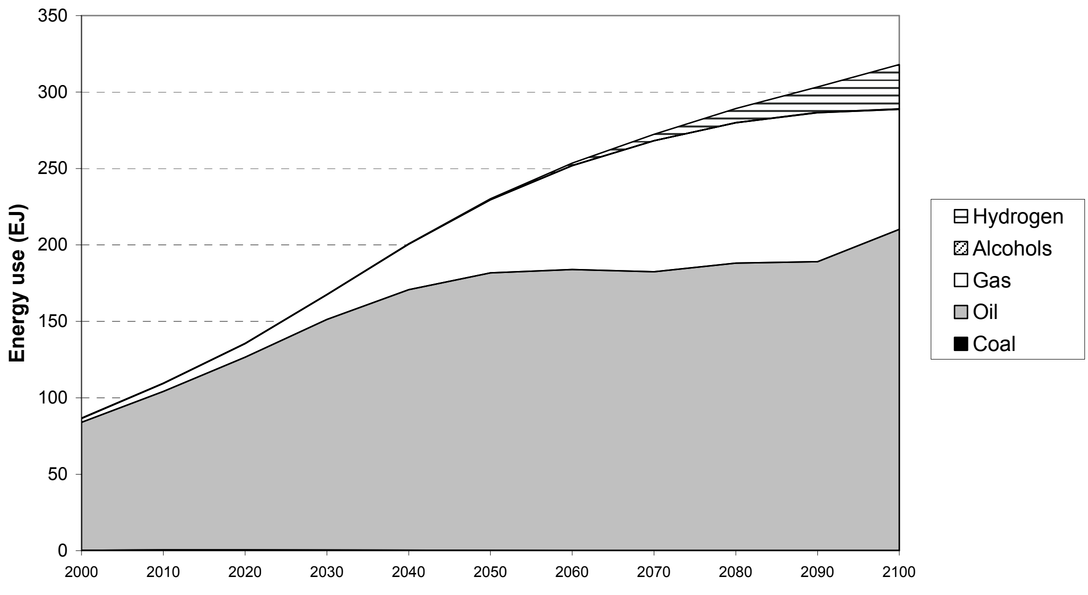

Figure 5-5 Global transport energy consumption, business-as-usual baseline

We now examine the impact of the various policy instruments described in Section 5.3 on this baseline scenario, and their impact on supply security, GHG emissions, energy system cost and the development of a "hydrogen economy".

5.4.2 Security of supply and climate change policy scenarios

5.4.2.1 Supply security

To measure long-term regional supply security, we use the resources to consumption ratio (Rsc:C). This is conceptually similar to the often-used resource (or reserves) to production ratio (R:P) (see, for example, BP 2004), however the Rsc:C incorporates import dependence. It must be noted, however, that this is an indicator of longer-term physical dependence, which may differ from economic dependence and vulnerability (for a discussion, see e.g., Kendell 1998).

Figure 5-6 presents the aggregated Rsc:C for crude oil for the regions considered to be most susceptible to a supply shock (OECD, EEU, CPA), under five policy scenarios. As is expected, the impact of the supply security policy (with and without a GHG cap) is to increase the aggregate Rsc:C relative to the baseline scenario. This impact is most pronounced in the second half of the century when oil becomes scarce. Figure 5-6 also shows by how many years the ratio is increased by the application of the supply policy. By the end of the century the supply policy increases the longevity of regional oil reserves by more than 16 years compared to the baseline scenario (and by more than 18 years if added to the GHG abatement cap scenario).

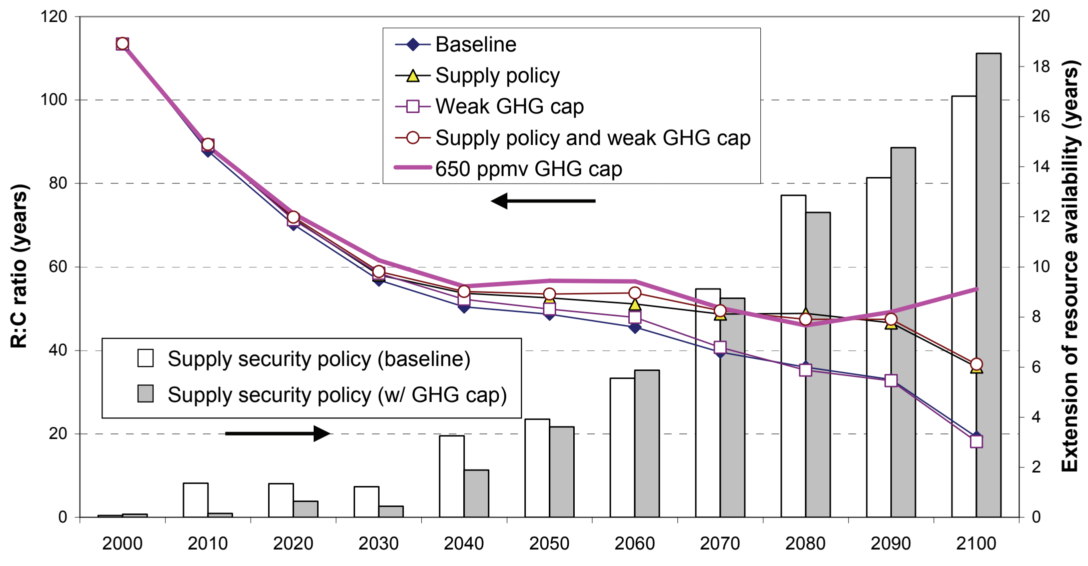

Figure 5-6 Resources:consumption (oil) for 5 regions, and extension of resource availability under security of supply policy

Five regions comprise: North America; Western Europe and Turkey; Eastern and Central Europe; Pacific OECD; and Centrally Planned Asia.

Looking at the impact of the climate change policy, Figure 5-6 shows that the weaker GHG cap alone does not significantly affect the aggregate Rsc:C ratio under the assumptions applied in this scenario. This occurs because of the relative attractiveness of oil compared to coal under this GHG abatement policy. Aggregate global coal consumption decreases by approximately 35 percent over the century with this policy compared to the baseline scenario, and it is necessary to maintain oil consumption in order to supply primary energy requirements. Only under the 650 ppmv abatement policy is oil availability extended in the regions most susceptible to a supply shock. It should be noted that this abatement policy is as effective as the security of supply policy at improving oil availability, and possibly more effective towards the end of the century. Accordingly, we do not present the combination of this abatement policy with the security of supply policy because this stringent abatement policy is already effective at ensuring the security of supply for oil.

The impact of the policies on global production of gas and oil is presented in Figure 5-7, which shows that the supply security policy increases gas consumption slightly during the first half of the century and reduces oil consumption throughout the century. This occurs because oil is relatively scarcer than gas, and by exploiting additional gas resources the supply availability of oil can be prolonged. In the latter part of the century gas becomes increasingly scarce and consumption is reduced in the supply security scenarios. It should be noted that if the security of supply of oil and gas was required to be maintained over an even longer timeframe (for instance, into the 22nd century), it is possible that it may be more effective to use fuels other than gas to prolong the life of oil resources.

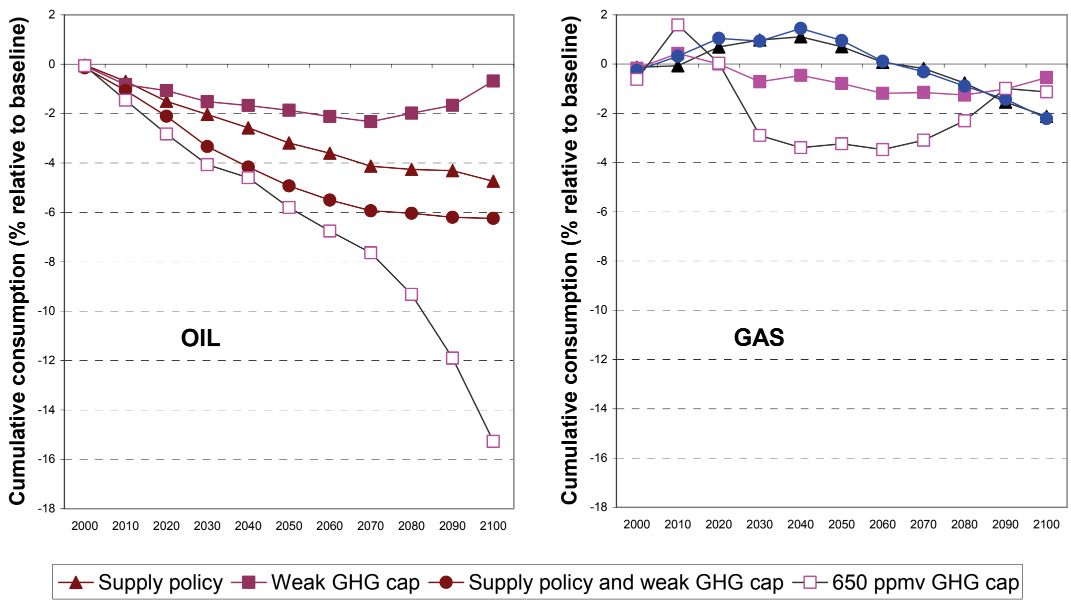

Figure 5-7 Cumulative global consumption of oil and gas, impact of policies relative to the baseline

Both of the GHG policies result in lower consumption of oil over the century, with the 650 ppmv policy resulting in a substantial decrease. However, neither policy appears to result in a significant shift to gas under the assumptions applied here, despite gas producing the least CO_2 emissions per unit of energy of all the carbon fuels. This is because gas is very attractive and is almost fully exploited in the baseline scenario, so there is little scope to increase gas use.[47] On the other hand, although the GHG abatement policies make gas more competitive compared to coal and oil, they also render some of the more expensive sources of gas less competitive relative to nuclear and renewable energy. The overall effect is seen in Figure 5-7, where cumulative global consumption of gas decreases slightly under the abatement policies, although by much less than oil consumption. It should be noted that even though gas consumption is lower for much of the century under the 650 ppmv policy, this policy is not effective at improving natural gas security of supply in the vulnerable regions.

Notably, the more stringent GHG abatement policy reduces oil consumption by more than any of the other policies examined, including the security of supply policy. Combining the weak GHG policy and the supply security policy increases the impact of the supply policy on oil consumption, but the combined effect is still lower than that of the more stringent GHG abatement policy. Gas consumption under the combined policy scenario follows a very similar trajectory to the path taken under the security policy alone. This reflects the relative flexibility and specificity of the policies, where there are many possible GHG abatement opportunities, but apparently few ways to maintain the Rsc:C.

5.4.2.2 Greenhouse gas emissions

The second policy outcome of interest is the level of GHG emissions. Figure 5-8 shows GHG emissions under the four policy scenarios relative to the baseline scenario. Under the weaker GHG cap, emissions are reduced to 26 percent below the baseline level by the end of the century, whereas under the 650 ppmv policy, emissions are reduced by more than 60 percent. As discussed, the baseline scenario represents a level of emissions in 2100 of almost three times 2000 levels, so the less stringent GHG cap scenario represents a case where emissions are still roughly 2.2 times 2000 levels by the end of the century.

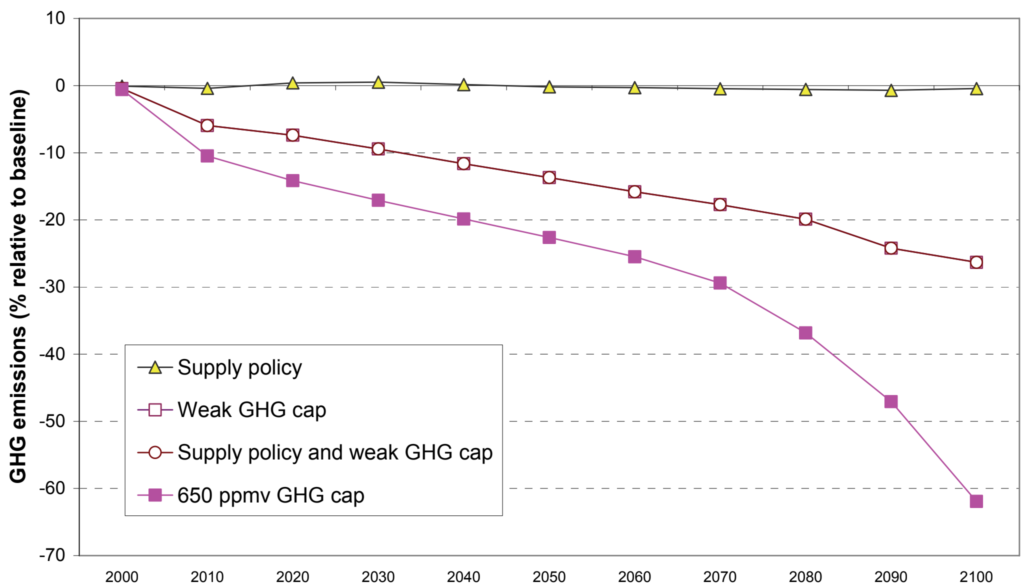

Figure 5-8 Global GHG (CO_2, CH_4 and N_2O) emissions, impact of policies

Note: the 'Weak GHG cap' and the 'Supply policy and weak GHG cap' curves coincide.

[47] This is also largely the case with a larger gas resource base which includes 5 percent of additional occurrences of gas. Only in three world regions (NAM, SAS and CPA) is gas use increased under the less stringent abatement target relative to the respective baseline scenario.

In the case of the supply security policy, emissions are roughly unchanged from the baseline scenario. An initial assessment of this result could be that pursuing a supply security policy neither supports nor discourages the uptake of abatement technologies. However, closer inspection shows that the security of supply policy encourages some technologies that reduce emissions (such as nuclear generation), some that potentially can reduce emissions (such as H_2-utilising technologies), and some that increase emissions (such as those that consume coal). The impact on emissions is roughly balanced. Some of these technologies are examined below.

5.4.2.3 Electricity generation

The policies examined here, targeted at different aspects of sustainable development, have the potential to significantly change the structure of the global energy system. This may be particularly so in the case of electricity generation, where a large number of alternative technologies are available that have the potential to both enhance energy security and reduce GHG emissions. Figure 5-9 shows the impact of the policies on the contribution of groups of technologies using different fuels to total global electricity generation over the century. Clearly, the GHG abatement policies have a much larger impact on the choice of fuel in electricity generation and result in the substitution of large amounts of coal with nuclear and renewable energy, although many of the more expensive renewable technologies are only competitive under the more stringent abatement policy. In comparison, the security of supply policy results in a small shift from gas generation to nuclear generation, with uranium assumed to be globally abundant. Combining the less stringent GHG policy with the security of supply policy appears to roughly add the impacts of the separate policies, except that the combined policy promotes generation from H_2 fuel cells.

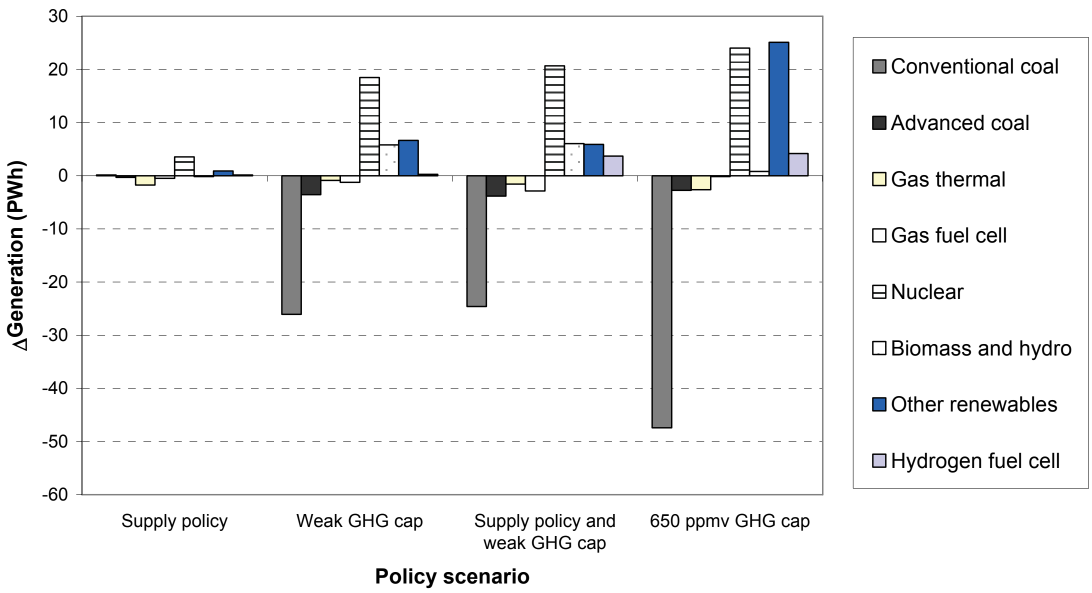

Figure 5-9 Impact of policies on total global electricity generation from different sources over the century

Generation from H_2 fuel cells is unnecessary under either separate policy because alternative sources of generation are available. However, the combined restrictions of the two policy instruments manifest as a requirement that both coal and gas use be reduced. The additional generation needed to overcome restrictions on coal and gas can only be obtained from a limited range of sources. Most medium-cost nuclear and renewable options are already exploited, leaving H_2 fuel cells as the next most competitive option, with the H_2 produced mainly from coal. Hydrogen fuel cells are also utilised under the more stringent GHG policy, where additional reductions in generation from conventional coal are necessary. Interestingly, under this GHG cap electricity generation from biomass is less attractive than under the less stringent cap. This occurs because under the more stringent GHG cap this biomass is needed for H_2 and alcohol production (for transport and some other stationary use).

5.4.2.4 Hydrogen production

One of the challenges facing policy-makers in improving security of supply is that the two scarce and unevenly distributed fuels—oil and natural gas—are also extremely flexible and convenient energy carriers. More geographically evenly distributed fuels, such as coal, uranium and many renewables are comparatively inconvenient and their conversion into flexible secondary carriers can be expensive today. However, an alternative flexible energy carrier than can potentially substitute for oil and gas in almost all applications is H_2. It is readily transportable and storable, can used with high efficiency in fuel cells, and has the potential to reduce GHG emissions if produced from renewable energy or from carbon fuels supplemented with carbon capture and storage (CCS) technologies. However, H_2 faces a number of barriers at all levels including production, distribution, storage and use (for example, see Service 2004, Keith and Farrell 2003, Turton and Barreto 2005), but the policies examined here may promote the development of a H_2 economy in some world regions.

Figure 5-10 shows global H_2 production under the five policy scenarios examined here. Under these scenarios, this H_2 is produced almost exclusively from coal and biomass, with coal predominating except under the abatement policy that stabilises atmospheric CO_2 concentration at 650 ppmv. This GHG policy has the largest impact on H_2 production, quadrupling aggregate production over the century relative to the baseline, mostly from biomass feedstocks. This H_2 is used throughout the energy economy, including in direct combustion applications and to power fuel cells in electricity generation and transport (where fuel cells dominate by the end of the century under this scenario). Interestingly, the weak GHG abatement policy reduces H_2 production relative to the baseline. This occurs because the abatement policy is strong enough to discourage coal-to-H_2 production, but not sufficiently strong to make synthesis from biomass, or carbon capture and storage (CCS) from H_2 production competitive (a similar result was seen in Section 4.2.2).

The supply security policy is also effective at increasing H_2 production under the assumptions used in the ERIS model, and this policy also increases consumption in all H_2-consuming sectors. The largest increase in consumption occurs in direct combustion of H_2 in the stationary sector, although there is also a substantial increase in consumption in the transport sector, where efforts to preserve resources and reduce consumption of oil make H_2 particularly attractive. Under the combined security-climate policy scenario, however, almost five times as much H_2 is used in electricity generation (as discussed in Section 5.4.2.3), with much less used in stationary direct combustion. Under this policy, the H_2 displaces GHG-intensive coal in electricity generation. This electricity production route is also favoured because the incremental costs of carbon capture from H_2 production are assumed to be lower than for capture from electricity generation (Socolow 2003).

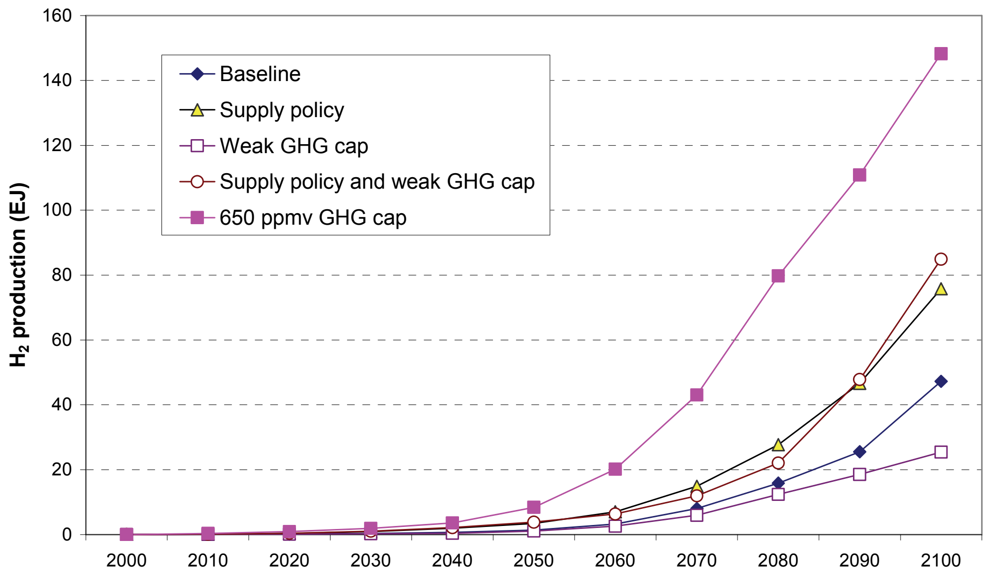

Figure 5-10 Impact of policies on global hydrogen production

To summarise, pursuing an energy policy that maintains supply security as modelled here, has the potential to accelerate the shift to a H_2 economy. The increased availability of H_2 under the security of supply policy may also provide some additional abatement opportunities. However, a stringent GHG abatement policy (that also achieves some supply security objectives—see Figure 5-6) has a greater potential to foster development of a H_2 economy, whereas a less stringent abatement policy discourages H_2 uptake under the assumptions used here.

Under all of the scenarios explored here, the energy system changes (such as additional H_2 production) required to achieve climate or security objectives are expected to be costly, and the economic cost of any policy is an important consideration in assessing its attractiveness compared to alternative options. We briefly examine the cost of the energy security and GHG abatement policies examined above in the following subsection.

5.4.2.5 Cost

It is useful to examine the impact on energy system costs of the different policies because it provides an indication of the availability and competitiveness of alternative energy resources that are either more abundant or less carbon-intensive. In addition, the marginal cost of combining two policies provides an indication of the extent to which the there are synergies between the policies in terms of impact on energy system development. The impact of the security of supply and the two GHG abatement policies on total discounted energy system costs is presented in Figure 5-11.

Figure 5-11 shows that the abatement policy designed to achieve stabilisation of atmospheric CO_2 concentrations at 650 ppmv is clearly the most expensive of the policies examined, mainly because it requires the adoption of many costly technologies, and a shift away from cheap sources of energy, notably coal. The weaker abatement policy is roughly 85 percent cheaper, and has a similar impact on cost as the security of supply policy, which is the basis upon which it was chosen for this analysis. Interestingly, the marginal cost of shifting to a combined security-climate policy from either policy alone is lower than the cost of pursuing the additional policy independently (the dashed region in Figure 5-11 shows the impact of simply adding the individual policy costs).

This is particularly interesting because the supply security policy does not reduce GHG emissions, and the less stringent GHG policy does not improve supply security. However, it appears that under the assumptions applied here there are some common impacts on the energy system, or synergies, between the two policies. The results in Figure 5-11 show that pursuing a supply security policy reduces the additional impact on the energy system cost of a GHG cap by approximately 16 percent, or pursuing a GHG abatement policy helps reduce the additional cost of maintaining supply security by around 22 percent compared to the security of supply-only scenario (equivalent in each case to reducing the combined policy cost by 9.1 percent, as in Figure 5-11).

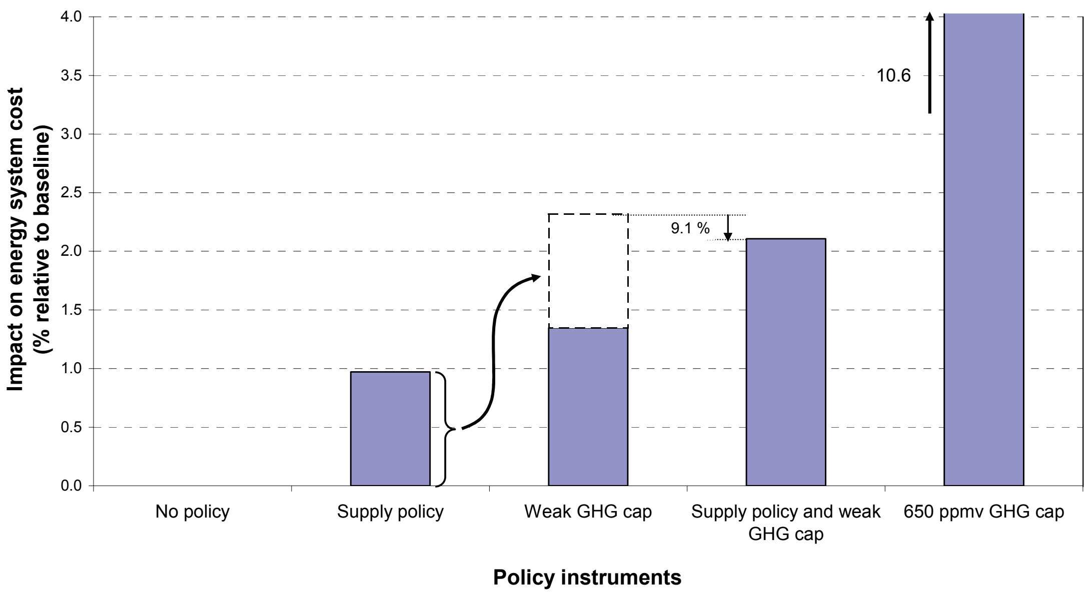

Figure 5-11 Impact of supply security policy and GHG cap on energy system cost

This indicates that although synergies exist between these two policy goals, they may be relatively weak. This is supported by the fact that there are not many significant energy system changes, relative to the baseline, common to both policies. The main ones comprise substitution of geo- and solar thermal energy for gas in district heating; an increased shift from conventional to hybrid-electric vehicles (HEVs); and increased production and use in transport of alcohol fuels. The impact on different electricity production technologies was presented in Figure 5-9, which highlighted the importance of nuclear energy under both policies. However, there are many significant and more substantial differences that add to the cost of the combined policy instrument. As mentioned earlier, coal consumption is one of the main differences, and the security policy results in much larger production of electricity, FT liquids and H_2 from coal than the less stringent abatement policy, which tends to favour nuclear and renewable electricity generation and use of gas. Further, although both policy instruments promote a shift away from conventional vehicles, in the security policy the shift is to gasoline and alcohol HEVs, whereas under the GHG tax policy the shift is to gas HEVs. These points of divergence highlight potential challenges of pursuing multiple sustainable development objectives simultaneously.

It should also be mentioned that, although not shown here, the marginal cost of adding the security policy to the 650 ppmv abatement policy is larger than of pursuing the security policy alone, even though this stringent abatement policy improves oil security (see Figure 5-6). This implies that the more stringent policy, although improving some aspects of security of supply, has greater negative impacts on other aspects, notably gas availability.

5.4.3 Technology policies

Technological change is likely to substantially transform the energy system over the long term and may potentially alleviate some of the risks associated with supply security and mitigate climate change, although market drivers alone may not be sufficiently strong to direct technological change towards these aims. Because the introduction of technologies and energy carriers that are not compatible with the dominating technological regime can be very difficult (Kemp 1997a,b), we have examined a series of policies focused on early deployment strategies for a number of emerging technologies.

We have targeted two energy supply technologies that are likely to be effective at promoting supply security because they use neither oil nor gas and produce a flexible energy carrier. The specific technologies examined are:

- advanced nuclear electricity generation (representing more efficient and inherently safe reactors, including passive safety systems that do not rely on sophisticated backups or operator experience), which may both enhance security of supply and reduce GHG emissions; and

- advanced coal electricity generation (IGCC), which utilises efficiently domestic resources to produce a highly flexible energy carrier. In addition, it is amenable to carbon capture and storage, which improves the ability of this technology to also contribute to GHG abatement,

To each technology we apply a deployment 'shock' policy, which involves providing $10 billion worth of the technology free to the energy system in the base year (2000) (see Section 5.3.3). These technology shocks are also combined with the supply security policies investigated in Section 5.4.2, with and without the less stringent GHG abatement policy to also investigate climate-security synergies of technology-specific measures.

5.4.3.1 Advanced coal generation

Figure 5-12 shows for each policy scenario the impact of the technology deployment shocks on discounted energy system cost. For comparison, Figure 5-12 also shows the cost in the absence of the technology policy (from Figure 5-11). A deployment shock targeting the IGCC reduces the cost of both the supply security policy and the climate policy when pursued separately. This D&D shock also reduces costs under a combined policy scenario. However, the additional cost of pursuing these policies together, compared to the baseline, is greater than the combined additional cost of pursuing each separately (Figure 5-12 presents the impact of simply summing the cost of the supply policy to the cost of the GHG policy as the dashed area).

This indicates that the changes that arise in the development of the energy system when the supply or climate policies are pursued separately are not cost-effective for pursuing a combined policy. Apart from indicating that there are relatively few synergies between these policies, this result also implies that the impact of this deployment shock depends on the policy environment, even though the shock favours IGCC generation regardless.

The trade-offs that arise under the different policies are illustrated by some of the differences in the energy system. Under the GHG abatement policy the technology deployment shock results in additional generation from IGCC power plants which displaces conventional coal generation. On the other hand, under the security of supply policy the additional generation displaces gas generation, enhancing gas availability. Under the combined policy, the conventional coal generation is displaced, but it is not possible to also displace the gas generation, requiring an alternative way of extending gas availability. This alternative manifests as additional H_2 and alcohol production, which is comparatively expensive and unnecessary when either policy is pursued independently.

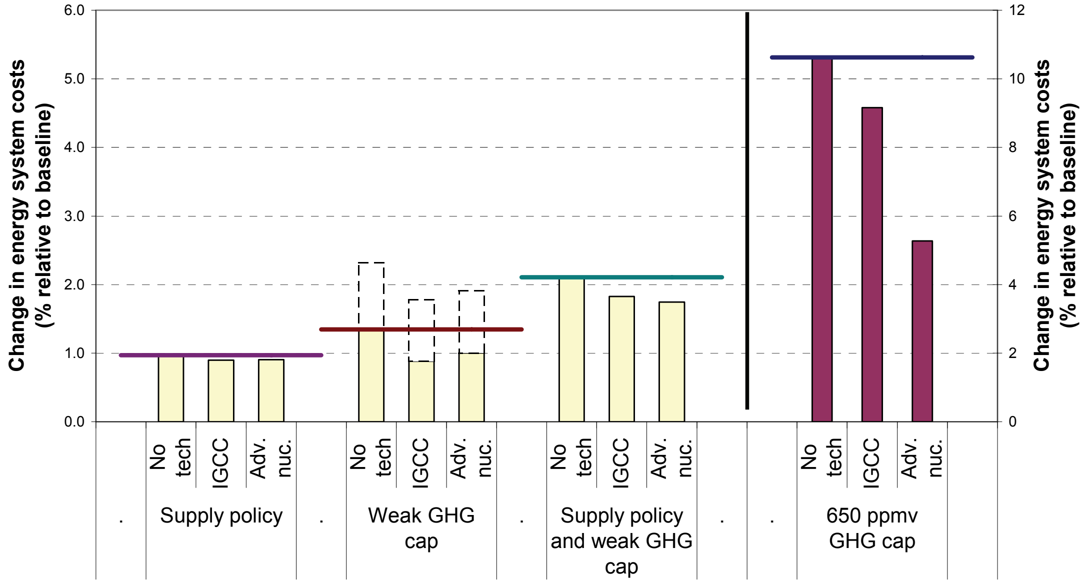

Figure 5-12 Impact of technology policies on the cost of security and GHG policies

Technology deployment 'shocks' also affect the energy system through spillovers to other technologies that use the same key components (see Section 3.3.6.1 in Chapter 3). However, there appear to be limited technology spillover benefits from the IGCC deployment policy, with the deployment shock leading to lower generation from other turbine-based technologies and reduced activity from gasifier-based coal-to-H_2 and coal-to-FT liquids production. Clearly, the impact of the deployment shock on the availability of other fuels more than offsets the impact of any spillovers to other technologies.

To summarise, a number of the effects of a policy promoting the deployment of advanced coal generation (IGCC) depend significantly on the policy environment, particularly whether there is a focus on either security of supply or climate change. This said, the shock still reduces costs under the combined policy scenario so is an effective instrument for achieving both policy outcomes together, or separately.

5.4.3.2 Advanced nuclear generation

Figure 5-12 shows that a deployment shock applied to advanced nuclear generation technology reduces system costs under all policies. The deployment shock has a strong impact on overall use of advanced nuclear generation, accelerating uptake and resulting in around 70 percent greater generation over the century under all policy scenarios. This occurs partly because the deployment shock makes this technology cheaper, but is mainly because the shock allows an accelerated roll-out of advanced nuclear capacity. However, what this large increase in capacity and generation displaces depends, once again, on the policy environment.

Under the climate change policy, the nuclear energy deployment shock displaces mainly conventional coal and wind generation, both of which are less attractive. Conventional coal is uncompetitive because of the GHG cap, whereas wind is more expensive because it is installed on a much smaller scale than advanced nuclear generation and is therefore assumed to benefit relatively less from learning-by-doing (also under the baseline scenario). However, this deployment scenario also results in some additional advanced coal generation. It should also be noted that this deployment shock has a dramatic impact on the costs of the more stringent GHG abatement policy (see Figure 5-12). This occurs mainly because, as mentioned above, the shock enables faster uptake of advanced nuclear capacity, which is a large-scale carbon-free energy source that is reasonably cost-competitive under this abatement scenario, even without the deployment shock.

Under the supply security policy, the additional nuclear generation displaces mainly gas generation, although some conventional coal is also displaced. Accordingly, unlike under the technology deployment policy targeting advanced coal generation, there are some similarities in the way the nuclear deployment policy affects the electricity sector under either policy.

With the combined policy, some conventional coal, wind and gas combined cycle generation are displaced. In addition, a large amount of H_2 FC generation is displaced, mainly by additional gas FC generation. The relatively large amount of electricity generated from H_2 fuel cells under the combined policy scenario (without a technology shock) was discussed in Section 5.4.2.3. The particular conditions that necessitated this high level of generation are changed by the technology shock, meaning that this expensive technology is no longer necessary, contributing to lower costs.

In contrast to the deployment shock for advanced coal generation, under the advanced nuclear generation deployment shock the cost of pursuing the supply security and greenhouse policies together is less than the sum of their costs when pursued separately. This result, combined with some of the similarities in development of electricity generation under the different policies, implies that a deployment policy for nuclear generation creates some synergies in terms of pursuing the other policy outcomes—security of supply and GHG abatement.[48] Or put another way, the impact of a deployment policy that supports advanced nuclear generation is less sensitive to the energy policy environment. The synergies between pursuing the two policy goals are not, however, substantially larger than in the absence of the deployment shock, although the overall costs are lower.

[48] Clearly, however, even the inherently safe advanced nuclear technology faces a number of other obstacles associated with waste disposal and public perception.

5.5 Discussion

5.5.1 Policy synergies and trade-offs

We have examined the trade-offs and synergies between supply security, climate change mitigation—two core elements of sustainable development—and technology-specific policies that promote the use of abundant indigenous resources. Synergies occur when actions are common to the two sustainable development policy goals, whereas trade-offs occur when the best ways of achieving the policies separately are very different and hence achieving the policy goals simultaneously is more challenging.

5.5.1.1 Synergies between security of supply and climate change mitigation policies

The nature of synergies and trade-offs between security of energy supply policies and climate change mitigation policies depend, in part, on the strength of the GHG abatement policy signal. Pursuing a stringent GHG policy may also achieve many of the objectives of a security of supply policy with respect to oil, indicating that some strong synergies exist between these two policies in some areas. Both a stringent abatement policy and a security of supply policy promote a shift towards a H_2 economy and the adoption of fuel cells in many applications. However, these synergies appear directional in the sense that the cheapest way to achieve security of supply does not improve GHG emissions, but the cheapest way of achieving deep cuts in emissions does improve security of oil supply. By contrast, although there are positive synergies between a less stringent abatement policy and a supply security policy, there is still a significant additional cost associated with achieving both policy goals compared to a single goal, indicating that these synergies are weak. This implies there is a threshold level of abatement above which greenhouse policies begin to promote oil security. In contrast, gas supply security was not improved significantly by either of the GHG abatement policies, and appears to involve a greater trade-off under the more stringent abatement policy, mainly because of the lower emissions intensity of this fuel.

One of the main areas of synergy between all policies is the role of nuclear energy. This technology was selected as a candidate for a technology deployment shock, which was shown to affect synergies between the two policies. Some other observations regarding technology deployment policies are discussed in more detail below.

5.5.1.2 Technology policies can enhance or diminish synergies

As discussed in the results, new and advanced technologies have the potential to help achieve a given policy outcome (for instance, security of supply) for a lower cost. However, the results also show that it is important to consider the extent to which the choice of technology for policy support may limit flexibility to pursue additional policy goals (such as climate change mitigation).

For example, it was also observed that the IGCC technology deployment shock increased the incremental cost of adding a climate change policy to a security policy, compared to the case without the deployment shock. This implies that the shock resulted in more divergence in the development of the energy system under the different policies. This highlights the potential for a technology support program pursued within an incomplete policy framework to entrench a particular energy system that has less flexibility to respond to other policy challenges. Where there is scientific, geopolitical or policy uncertainty about future costs it is prudent to maintain a flexible energy system that can respond to new information or unforeseen events.

However, it was also observed that this technology may be relatively more attractive under a more stringent GHG abatement policy, which highlights the importance of setting a clear policy goal as early as possible. Balancing the need for policy clarity and flexibility when pursuing sustainable development is a major challenge for policy-makers.

The interaction between technology and other policies also highlights the importance of co-ordinating technology-push and market-pull—that is, technological development alone will not necessarily result in the best social outcome, particularly where market imperfections promote the use of a technology in undesirable ways.

5.5.2 Long-term supply security

Assumptions about the size of ultimately recoverable resources of oil and gas play a key role in determining how best to maintain medium- to long-term energy security. Under the assumptions used in this dissertation, total oil and natural gas resources are large but unlikely to last much beyond the end of the 21st century under the demand scenario applied here.[49] Even assuming that some of the additional occurrences of natural gas become commercially extractable, gas consumption is still likely to peak this century. In other words, the global supply of gas and oil is 'insecure' over the longer term and a transition to other primary fuels is necessary, regardless of short- to medium-term supply risks. Consequently policies that improve supply security are effectively accelerating the necessary long-term transition away from these fuels.

Further, restricting the application of the security policy to 100 years, as was done here, has a number of additional implications for the findings. In particular, one result observed under the security of supply policy was that the availability of oil could be prolonged by exploiting additional natural gas resources early in the century. In the analysis here, there was sufficient natural gas to achieve the requirements of the security policy, even accounting for this higher gas use initially. However, if it were necessary to maintain security of oil and natural gas supply over a longer timeframe (beyond the 21st century), it may no longer be attractive to use gas to prolong the availability of oil, because this reduces the very long term availability of gas. Accordingly, the period over which supply security needs to be maintained may have an impact on the choice of fuels and hence technologies.

5.5.2.1 Security of supply and resource sustainability

It is apparent that long-term supply security has a number of features in common with broader long-term sustainability given that it represents one element of sustainable development, although important differences exist (Schrattenholzer *et al.* 2004). The most notable feature in common is that indefinite maintenance of supply security must ultimately manifest as sustainable resource consumption, eventually requiring a shift to renewable resources over the very long term. So a shift from oil and natural gas to a combination of coal, uranium, biomass and other renewables should be seen as the first step in a centuries-long transition. The model used here is capable of shedding some light on relevant aspects of this very long-term transition. Where broader sustainability and supply security diverge is that the latter considers only the impact of resource availability, and not the impact of consumption, such as the

[49] The amounts assumed in this dissertation are either above or roughly in line with other estimates (for example, see Odell 2004). We do not consider the possibility of repletion of existing fields with abiogenic oil or natural gas.

harmful by-products, or all competing demands, either natural, intragenerational or intergenerational.

Importantly, however, policies that promote supply security alone may go some way towards promoting broader sustainability goals, such as by reducing GHG emissions, or at least reducing the cost of pursuing future abatement, as long as these policies promote a shift to low carbon primary energy resources. In addition, policies that realise security of supply may contribute to the social, economic and political stability that are pre-conditions for the implementation of policies needed to achieve other elements of long-term sustainability. We examine the impact of pursuing multiple sustainable development objectives—including supply security—in more detail in Chapter 7.

5.6 Conclusions

The analysis presented in this chapter seeks to compares the costs and impacts of managing two substantial uncertainties facing the energy system:

- the risk of a disruption to energy supply; and
- the risk of anthropogenic climate change.

Managing these risks is an important element in long-term sustainable development, because incorrect policy decisions may potentially result in large economic and social costs. Accordingly, policies that effectively manage and reduce these risks may result in very large social benefits. We have compared risk management strategies that enhance long-term energy security of supply and reduce GHG emissions, at varying cost. We have also examined how these policies may interact, and the role of particular technologies in pursuing these policy goals. It must be emphasised that in all cases the relative social benefits from these policies on either energy security or climate protection are uncertain, although maintaining supply security may be perceived to be of more immediate concern (Frei 2004). Nonetheless, the results may provide some guidance for policy makers when comparing the need to maintain security of energy supply and avoid some of the impacts of climate change.

Importantly, we have observed that efforts to manage one of these risks may actually reduce the costs of managing the second risk. That is, there are some synergies in a combined policy environment, but the interaction is not simple. Moreover, there may be risks associated with pursing one policy goal whilst ignoring the other, which may lock the energy system into a particular development path, limiting its flexibility to respond to uncertain future challenges. Technology deployment policies can influence the efficacy of energy security and GHG abatement policies, but simultaneously the impact of these policies on the energy system also depends in large part on the broader policy context.

It should also be noted that the available risk management options for these two policy goals are restricted in the study presented in this chapter. For example, short-term political or diplomatic actions are not represented, nor are options related to adaptation, to either climate change or a supply disruption. However, the most notable omission is the exclusion of reductions in energy demand in response to policies designed to address security of supply or climate change (and nor is reducing demand modelled as a policy itself). This approach has the advantage that it focuses the analysis specifically on the role of fuel mix and technologies, and highlights the implications of attempting to manage these risks without reducing energy demand. Nonetheless, demand reductions are likely to play a critical role in addressing both climate change mitigation and security of energy supply, and in realising a sustainable energy and transport system over the long term. Accordingly, in the following chapter the modelling framework constructed in Chapter 3 is extended to incorporate a price response into energy demand decisions. This is important in the development of the policy analysis tool described in the dissertation, since it facilitates a more complete assessment of the impact of alternative scenarios or policy instruments.

Chapter 6. ECLIPSE: an integrated energy-economy model for climate policy and scenario analysis

6.1 Introduction

Energy is an essential input to the operation of economies worldwide. Not only is energy required by essentially all production processes, it is also used in significant amounts directly by final consumers for transport and household services. The close relationship between economic activity and energy use means that factors affecting energy availability and price also affect the rest of the economy and, *vice versa*, economic activity impacts the energy sector. Moreover, many of the policy challenges confronting the energy sector have important implications for the economy as a whole.

An essential role of the policy-maker is to attempt to predict the impact of existing and prospective policies on future social, economic and environmental well-being. The ability to estimate accurately the impact of a given policy increases the likelihood that the most suitable policy instruments are adopted, assisting governments in allocating their and society's scarce resources in the most effective and efficient manner. One of the most significant challenges facing policy-makers this century is responding to anthropogenic climate change by reducing greenhouse gas (GHG) emissions (see, for example, IPCC 2001e). Many GHG abatement policy instruments affect the energy sector in particular, but also have implications for other economic sectors both directly and because of other more complex energy-economy interactions.

However, climate change mitigation is just one of the challenges confronting policy-makers, and formulating an appropriate response is confounded by uncertainty regarding how future global economic activity and energy demand will unfold. The impact of the ubiquitous process of technological change on both economic development and specific energy technologies (Maddison 1993; McDonald and Schrattenholzer 2001), the possible emergence of a sustainable global energy system or hydrogen economy (Barreto *et al.* 2003), and the possibility of economic "catch-up" by less developed world regions all potentially have major implications for energy demand and the effectiveness of policy intervention. The reemergence of concerns about security of energy supply reflects another significant uncertainty affecting the future energy system (Turton and Barreto 2006).

To cope with these uncertainties, effective policy-making requires flexible integrated assessment tools that can assess a range of scenarios and evaluate the effect of different policies, including those for climate change mitigation. Many sophisticated tools have been developed to assist the policy-maker explore the impact of potential policies and measures on future climate, economic and energy system variables (for an illustration of the models used by the IPCC in scenario and policy analysis, see Nakićenović and Swart (2000) and IPCC (Metz *et al.* 2001)). However, some of these lack the flexibility to cope with the significant levels of uncertainty which are inherent in future scenario and policy analysis. For analysing a wide range of greenhouse gas abatement scenarios and policies, for example, and assessing the potential of energy generation and abatement technologies in a consistent way, a fast, flexible and transparent tool is essential.

This chapter discusses the development of such a flexible policy analysis tool—called the ECLIPSE (Energy and Climate Policy and Scenario Evaluation) model—based on extending and enhancing the modelling framework presented in Chapter 3, based on the ERIS (Energy

Research Investment Strategy) bottom-up energy systems model. Like ERIS, the ECLIPSE model is designed for exploring long-term (to 2100) interactions between energy and transport systems and the broader economy, on a global 11-region scale. To overcome the limitations of bottom-up modelling—namely the failure to adequately represent the linkage between energy demand and the economic forces ultimately driving demand (including demand elasticity)—in ECLIPSE we link ERIS with a reduced-form top-down economic model and solve it iteratively. This builds on and enhances similar approaches applied by Messner and Schrattenholzer (2000), Kypreos (1996), Manne *et al.* (1995) and Manne and Wene (1994), and here we combine the strengths of these earlier approaches with a number of additional features that provide additional insights and extend the robustness of the model output. Using a detailed energy system model with technology learning, such as ERIS, also ensures that the key weaknesses of top-down modelling—namely, the inability to represent the impact of specific technology options in detail—are avoided. Moreover, additional features are included here to address the second thematic focus of this dissertation on the transport sector, particularly passenger transport. Specifically, this chapter describes an alternative approach to representing drivers of transport demand and technology, drawing on the methodology applied in developing the passenger transport scenario presented in Section 3.2.2 of Chapter 3 (see also Turton and Barreto 2005).

Furthermore, it should be mentioned that the ECLIPSE policy assessment tool presented in this chapter retains all of the features already described in Chapter 3. For example, the assessment of climate change uncertainty is facilitated by the linkage to the MAGICC climate model (see Section 3.3.7 in Chapter 3; Hulme *et al.* 2000; Wigley and Raper 1997; Wigley 2003). This combined modelling framework is designed to be highly flexible and capable of assessing a wide range of scenarios and policies. It achieves this flexibility and speed principally by forgoing the high levels of energy system detail in a model such as MESSAGE (Messner and Strubegger 1994), or economic detail in a general equilibrium model (such as EPPA (Babiker *et al.* 2001). In this way ECLIPSE has more in common with a model such as MERGE (Manne *et al.* 1995), although with more detail in both the energy and economic systems.

The remainder of this chapter is divided into three main sections. Since this is principally a methodological chapter, the largest of these sections (Section 6.2) is devoted to the description of the development of the ECLIPSE model. It is divided into subsections on the ERIS model (6.2.1) and the macroeconomic and transport demand models (6.2.2 and 6.2.3, respectively) to which it is linked. This linkage is discussed in detail in Section 6.2.4. Section 6.3 then presents some results from the ECLIPSE model, with the first subsection (6.3.1) illustrating technical characteristics of the convergence of some selected model outputs. Section 6.3.2 then illustrates some features of ECLIPSE that represent important improvements in model calibration over some earlier approaches, followed by Section 6.3.3 which presents results comparing ECLIPSE with the bottom-up ERIS model to illustrate some advantages of combining top-down and bottom-up models. Sections 6.3.4 and 6.3.5 present results for some simple GHG mitigation scenarios to illustrate how the model performs with a real policy scenario, and discusses some preliminary policy insights. The main conclusions from this analysis are discussed and summarised in Section 6.4.

6.2 Modelling framework

6.2.1 The ERIS model

The ERIS model, including its linkage to the MAGICC climate model is described in detail in Chapter 3. Accordingly, to avoid repetition here, we briefly highlight some of the relevant features of ERIS. The most critical feature to note is that ERIS determines the optimal least-cost mix of energy sources and conversion technologies to meet a given demand for energy and transport services. However, demand in ERIS is inelastic with respect to energy price, unlike in real energy systems, thereby reducing the model's suitability for assessing the full impact on the energy system of policy instruments (such as emissions taxes and trading schemes, R&D programs, generation portfolio standards and others) and other factors (such as resource constraints). Accordingly, given that one of the main aims of this dissertation is to develop a relatively widely applicable integrated policy assessment tool, this chapter outlines modifications and additions to the ERIS framework presented in Chapter 3 which overcome the limitation of demand inelasticity, by incorporating a price response. This is achieved in ECLIPSE by linking ERIS to a macroeconomic model that determines the quantity of energy demanded by the non-energy economy (since the ERIS model already covers the energy economy), based on energy prices.

As mentioned, ECLIPSE is based on similar spatial and time horizons as the ERIS model—that is, ECLIPSE is a global 11-region model designed for exploring long-term (to 2100) interactions between energy and transport systems and the broader economy. Given these time and spatial horizons, and the associated high levels of uncertainty, a fairly stylised macroeconomic model is applied, as described in the following subsection. Moreover, to simplify solving of this model, we use time steps of 10 years over the 100-year time period of interest (the model is usually solved over a 150-year horizon to avoid any possible boundary effects in later years of interest).

6.2.2 Macroeconomic features of ECLIPSE

6.2.2.1 The macroeconomic model

Previous work by Messner and Schrattenholzer (2000), Manne *et al.* (1995), Manne and Wene (1994) and Kypreos (1996) has guided the development of the macroeconomic model, which is linked with the ERIS model in ECLIPSE. Like the other models cited, the primary purpose of ECLIPSE is to represent the impact of changing energy costs and prices (arising from policy or market changes) on economic activity, and changes in energy demands in response to energy price changes. Accordingly, it is not the intention to construct an endogenous growth model, or develop a new method to link economic growth and energy demand. Instead we begin by adopting a similar approach to that applied in MERGE, MESSAGE-MACRO and MARKAL-MACRO (Messner and Schrattenholzer 2000; Manne *et al.* 1995; Manne and Wene 1994; and Kypreos 1996); to model the impact of energy price changes on a *predefined* scenario of population, economic growth and energy demand, including demand for different energy services.

On this basis, the macroeconomic model in ECLIPSE first requires inputs from a reference scenario of economic growth and energy (and transport) demands from another source, such as the IIASA[50] Scenario Generator—a simulation model that formulates scenarios of population, economic and energy development for the eleven world regions analysed by ERIS and MESSAGE (Nakićenović *et al.* 1998). Since the purpose of ECLIPSE is then to explore how this reference economic and energy trajectory responds to changes in energy prices arising from policy or other market changes, it is also necessary to define an accompanying reference energy price path. This future energy price trajectory path is, by definition, consistent with the reference economic growth and energy demand scenario.[51] We return to our assumptions regarding this price pathway later in this chapter.

The model presented here therefore requires as inputs from an exogenous scenario: a reference economic growth; and a reference set of energy (and transport) demands—from which a reference energy efficiency improvement (REEI) can be estimated. In addition, a reference energy price scenario is required. Critically, this approach necessitates that the macroeconomic model be defined in a way that is consistent with the reference scenario—specifically, that it is able to reproduce reference growth and demands under reference prices. We now turn to the representation of macroeconomic growth, but return to these parameterisation requirements below.

6.2.2.2 The economic production function

The basic economic model is defined in a similar way as in the models MERGE and MESSAGE-MACRO (Manne *et al.* 1995; Messner and Schrattenholzer 2000). That is, we consider separately the output of the energy system (modelled by ERIS), and the output of the rest of the economy. Final energy and transport are produced by the energy sector and consumed by the rest of the economy, linking these two production activities.

Using a simplified input-output (I-O) framework, the aggregate economic output of the non-energy sector (Y_t) can be formulated as the sum of value-added in the non-energy sector ($VA_{ne,t}$) and inter-industry payments for energy and transport services. These inter-industry payments comprise the sum of energy sector value-added ($VA_{e,t}$) and the costs of energy and transport service production (EC_t). Accordingly,[52]

$$Y_t = VA_{ne,t} + VA_{e,t} + EC_t \tag{6-1}$$

(noting that $GDP_t = VA_{ne,t} + VA_{e,t}$)

The overall macroeconomic modelling framework is presented schematically in Figure 6-1, and we describe the key elements below.

[50] International Institute for Applied Systems Analysis.

[51] The reference economic growth scenario and the accompanying reference energy demand scenario can together be used to define a consistent energy intensity scenario. Returning to the concept of reference energy prices, this reference energy intensity scenario describes the energy efficiency improvements consistent with the reference energy price trajectory. *Ceteris paribus*, if energy prices increase more rapidly than the reference price scenario, one would expect faster energy intensity improvements, and *vice versa*.

[52] Note, although as discussed ECLIPSE is an 11-region model, for simplicity equations are presented without a region index.

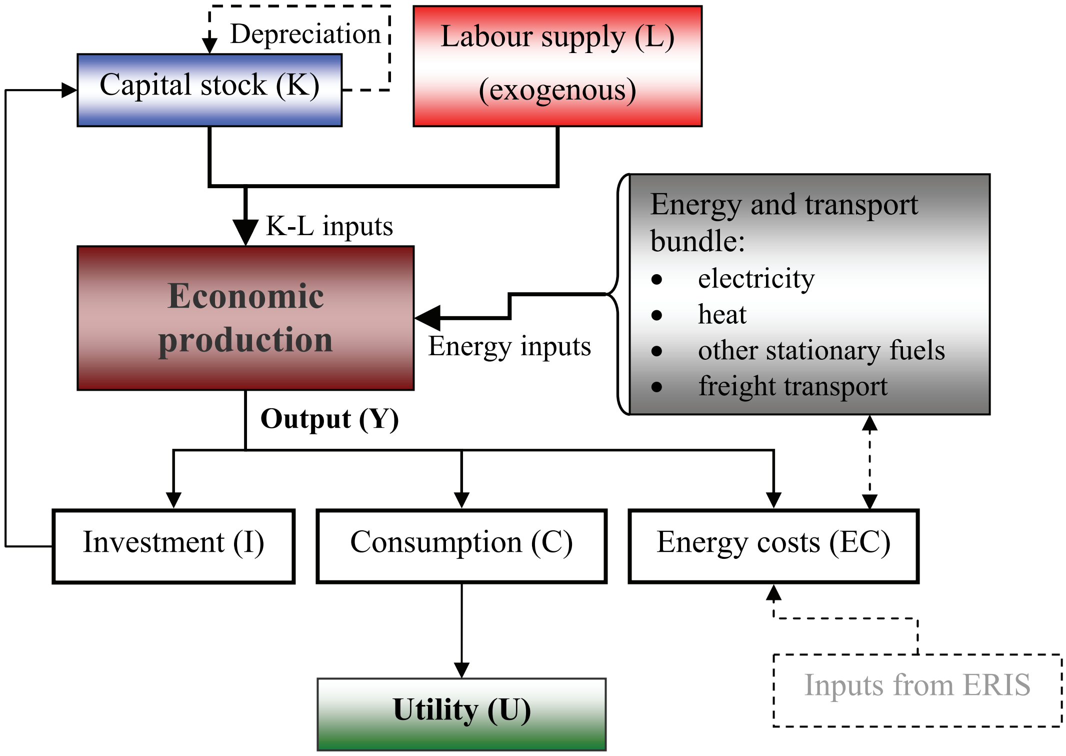

Figure 6-1 The macroeconomic model

Note: For each world region, the model determines investment (I), consumption (C), and energy and transport inputs, so as to maximise discounted utility (sum of discounted U).

The production of non-energy economic output (Y_t, hereafter referred to simply as economic output) is modelled using a simplified production function similar to that used in MERGE and MESSAGE-MACRO (Manne *et al.* 1995; Messner and Schrattenholzer 2000), although with a number of important modifications. This production function is defined with constant elasticity of substitution ($\sigma = 0.4$ in developed world regions and 0.3 in developing regions, as in MESSAGE-MACRO (Messner and Schrattenholzer 2000)) between nested non-linear Cobb-Douglas functions of capital (K_t) and labour (L_t) and energy and transport ($energy_j$):

$$Y_t = \left[a \bullet a_{corr_t} \bullet K_t^{\alpha\rho} \bullet L_t^{(1-\alpha)\rho} + b \bullet b_{corr_t} \bullet \prod_j \left(\frac{energy_{j,t}}{\eta_t} \right)^{share_{j,t} \bullet \rho} \right]^{\frac{1}{\rho}} \qquad (6\text{-}2)$$

where $\rho = (1 - 1/\sigma)$ and j indexes the set comprising electricity, heat, other stationary energy and freight transport. The other parameters in the production function include α, the optimal value share of capital in the capital-labour bundle and $share_{j,t}$, the optimal value share of energy or transport input j in the energy-transport bundle. Reference scenario energy efficiency improvements (REEIs) that affect all energy inputs are accounted for with η_t (≤ 1), which reflects cumulative improvements since the base year. The terms a and b are calibration parameters, and are calculated assuming that first-order optimality conditions are satisfied in the base year (for which many of the production function variables are known). These conditions require that additional units of each production factor are used up to the point where the marginal product of the production factor (i.e., the partial derivate of the production function with respect to the factor) is equal to its price. For the base year it is assumed that the actual quantities have been determined according to this condition, allowing the *a* and *b* parameters to be determined.[53]

Of the remaining production function parameters, the $b_{corr,t}$ factors are included to ensure that REEIs do not lead to an artificial rebound in economic output that would be inconsistent with the reference scenario under reference prices.[54] The $a_{corr,t}$ factors are necessary to ensure that constant returns to scale from one time period to the next are maintained after the $b_{corr,t}$ factor is applied.[55] It is important to note that in ECLIPSE, as in MERGE and MESSAGE-MACRO, the $b_{corr,t}$ (or equivalent) correction factors are parameterised on the basis of the *average* energy intensity of total output and the *entire* capital stock (both old and new). In ECLIPSE these 'average' factors are then applied in calculating total output in each period. In contrast, in MERGE and MESSAGE-MACRO, these 'average' coefficients are applied to determine energy requirements of *new* vintages of capital. This approach appears to be inconsistent with the reference scenarios upon which the calibration of these models is based—a consistent approach would be to apply correction factors reflecting energy intensity of new vintages (which one would expect to be significantly lower than the average energy intensity of the capital stock)—implying that these other models may underestimate autonomous energy efficiency.[56] We illustrate the improved approach in ECLIPSE in Section 6.3.2.2.

The production function in Eq. (6-2) also differs from the MESSAGE-MACRO and MERGE functions (see Messner and Schrattenholzer 2000; Manne *et al.* 1995), in that it includes a more disaggregated 'energy-transport' bundle. Energy inputs are disaggregated in ECLIPSE to account for the fact that different energy services are not perfect substitutes, as in MARKAL-MACRO although with a different formulation resulting in different substitutability between inputs (Kypreos 1996; Manne and Wene 1994). In contrast, treating all non-electric demands in aggregate—as in MESSAGE-MACRO and MERGE—implies that a unit of either thermal, low-quality heating, or transport energy has the same impact on

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[53] For example, the first-order optimality condition for electric energy is:

$$p_{E,t} = \frac{\partial Y_t}{\partial E_t} = \frac{1}{\rho} \bullet share_{elec,t} \bullet \rho \bullet b \bullet b_{corr_t} \bullet Elec_t^{-1} \bullet \prod_j \left(\frac{energy_{j,t}}{\eta_t}\right)^{share_{j,t} \bullet \rho} \bullet Y_t^{1-\rho}$$

where $p_{E,t}$ is the price of electric energy. In the base year all the other variables in the function are known, so it is straightforward to estimate *b* (actually *b* * b_{corr}—this is discussed below). The parameter *a* can then be determined from Eq. (6-2).

[54] That is, the b_{corr} factor ensures the model is able to reproduce reference demands and economic activity under reference prices. Rebound effects resulting from alternative energy price scenarios are potentially a very important determinant of energy demand, and are represented fully in the model. The b_{corr} factors are defined for each time period according to first-order optimality conditions under the reference scenario, similar to the way the equivalent factor is defined in the latest version of MERGE (Manne and Richels 2004).

[55] The inclusion of $b_{corr,t}$ factors that can vary from one time period to the next means that the production function no longer necessarily exhibits constant returns to scale between time periods. If $b_{corr,t}$ decreases from one time period to the next then increasing all inputs proportionally (with a different proportion for energy inputs to account for REEIs and changes in value shares) results in a disproportionately larger increase in total output, and *vice versa*. Accordingly, the $a_{corr,t}$ factor is included to restore constant returns to scale between periods (while still accounting for the impact of REEIs and changes in value shares).

[56] Despite problems with the application of reference efficiency improvements in MERGE and MESSAGE-MACRO, there are a number of arguments in favour of the general approach of considering energy intensity improvements for only new vintages, particularly for fixed capital investment. However, it is perhaps unreasonable to assume that the energy demand from older vintages of capital is unresponsive to changes in energy prices—as in MERGE and MESSAGE-MACRO—since the energy consumption of fixed capital stock is determined partly by operational practices and complementary systems, and can in some cases be changed with relatively cheap retrofitting. For this reason the model described in this chapter considers the energy intensity of the capital stock in aggregate (consistent with the reference energy intensity scenario), although we accept that alternative approaches may be worth exploring.

economic output. To avoid this unrealistic representation, non-electric energy is disaggregated in ECLIPSE to create a separate stationary energy demand category accounting for low-quality thermal demand for space and water heating, supplied by cogeneration, solar thermal water heaters, geothermal hot water, and specific direct-combustion technologies (see Section 3.3.3 in Chapter 3). Non-electric energy is further disaggregated to also create a separate freight transportation input to the production process. Freight transport can be substituted with capital and labour—that is, more expensive (i.e., more capital and labour-intensive) products can be sourced from nearby producers instead of from cheaper (i.e., less capital and labour-intensive) but more distant producers. Similarly, transport can be substituted for energy—for example, agricultural output could be produced in a subregion with a warm climate and transported to demand centres in a cooler subregion, or grown in an artificially-heated greenhouse in the cooler region.

The inclusion of separate heat and freight transport inputs means that there are three distinct non-electric demands in the ECLIPSE production function. This disaggregation also improves the consistency between the top-down and bottom-up components of ECLIPSE, by ensuring they have the same number of demand sectors and thereby taking full advantage of the demand and technology detail in the ERIS model. A similar approach is applied in MARKAL-MACRO (Kypreos 1996), but models such as MESSAGE-MACRO introduce an additional step to translate changes in aggregate non-electric energy demand into changes in disaggregated energy service demands (Messner and Schrattenholzer 2000; Messner and Strubegger 1994), whilst MERGE does not include a comparable level of technology detail in its representation of the energy system.

In addition to employing a greater level of disaggregation in the ECLIPSE production function, some energy services are excluded altogether—specifically, energy used in passenger transport. This alternative treatment is warranted because energy used for passenger transport can be considered to be a consumption good, rather than an input to production, and we discuss how this service is modelled in more detail in Section 6.2.3.[57]

Looking now at the use of economic production in the economy, output is allocated between consumption (C_t), investment in the capital stock (I_t), and to payment of energy costs (EC_t) (refer to Figure 6-1).

$$Y_t = C_t + I_t + EC_t \tag{6-3}$$

The objective of the model is maximisation of the aggregate utility of consumers over the timeframe of interest. An individual consumer's utility is assumed to be a log function of consumption, hence with decreasing marginal returns. Aggregate utility is given by:

$$\begin{aligned} Utility(U) &= \sum_t Pop_t \bullet PCU_t \bullet UDF_t \\ &= \sum_t Pop_t \bullet \log_e\left(\tfrac{C_t}{Pop_t}\right) \bullet UDF_t \end{aligned} \tag{6-4}$$

where PCU_t is per capita utility, Pop_t is the population, C_t is aggregate consumption and UDF_t a utility discounting factor. This approach of maximising utility in each region

[57] A similar argument could be used to support an alternative treatment of all residential sector energy demand. This is an area of potential future improvement.

separately diverges somewhat from the approach used by Manne *et al.* (1995) who applied an objective function concerned with maximising Negishi-weighted global utility (Manne and Richels 2004). The Negishi factors in MERGE, however, are designed to satisfy inter-temporal trade constraints rather than necessarily account for differences in relative welfare in each region. In comparison, the approach in ECLIPSE avoids the difficult task of weighting utility in different world regions and allows ERIS to determine energy trade based on least-cost criteria (see Section 6.2.1), with regions assumed to maintain a balanced trade account over the long term.

6.2.2.3 Additional inputs and calibrating the production function

The functions described in Eqs. (6-1)-(6-4), when combined with a simple capital stock function,[58] are together used to represent macroeconomic activity. However, it is important to recall that this tool is not itself designed to project key variables such as the growth in population and economic production capacity, nor the rate of autonomous energy efficiency improvement. Instead, ECLIPSE seeks to explore how the energy system responds to the influence of policy instruments or changes in other factors under a scenario in which these variables are already approximately defined.[59]

As discussed, the scenario inputs used in the analysis presented in this dissertation are based on the B2 scenario described in Section 3.2.1 in Chapter 3 (which was originally generated using the IIASA Scenario Generator (Nakićenović *et al.* 1998)). The key variables defined by the scenario presented in Section 3.2 (Chapter 3) for each world region include:

- population growth;
- reference (or potential) growth in GDP;
- reference energy efficiency improvements (REEIs); and
- physical shares of different energy and transport inputs.

The scenario variables are used to define, in Eqs. (6-2) and (6-4), population (Pop_t), the labour supply (L_t), cumulative REEI (η_t) and the values shares of inputs ($share_{j,t}$)[60] in the production function. In addition, the utility discount factors (UDF_t) in Eq. (6-4) are defined such that they reflect the preferences for consumption and investment (and hence future consumption) implied by the potential growth rate path. In other words, *UDF*s are defined

[58] The capital stock in the non-energy sector is treated in aggregate (all vintages) and changes as a consequence of investment (*I*) and constant depreciation (fixed at 5 percent per year). In the energy and transport sectors, specific technologies are represented, each with an effective operating life ranging from 10 to 50 years depending on specific technology characteristics (Turton and Barreto 2004; Kypreos *et al.* 2000; Barreto and Kypreos 2000; Barreto and Kypreos 2004).

[59] MESSAGE-MACRO and MERGE use a similar approach. However, this is a key point of departure with MARKAL-MACRO used by Kypreos (1996), where the first operation is to set REEIs for different energy services in such a way that demands, shadow prices from MARKAL and an assumed economic growth rate are all consistent. That is, here MARKAL-MACRO works backwards from demands to calculate REEIs assuming an equilibrium between starting demands and the assumed economic growth rate (Kypreos 1996). This is necessary only when the models used to define energy demands provide no information on expected economic output (and hence REEIs).

[60] Note, the physical shares of different energy carriers are converted to values shares by applying prices designed to reflect scenario features. That is, these are the prices under which the potential growth rates are achieved, and are called reference energy prices hereafter.

based on the same principle applied in calibrating other model parameters—that under reference prices, the reference economic growth trajectory and energy demands are realised.[61]

As a brief aside, one critical factor determining the *UDF*s which satisfy the above requirements is the marginal product of capital. In the case of MESSAGE-MACRO and MERGE (Manne *et al.* 1995; Messner and Schrattenholzer 2000; Manne and Richels 2004), an estimate of the marginal product of capital is used to determine *UDF*s, rather than the actual marginal product implied by the production functions used in these models. To illustrate the effect of the alternative approach employed in ECLIPSE, we explore the impact on the reference growth trajectory of varying the marginal product of capital in Section 6.3.2.

Returning to the scenario variables, all are assumed to be independent of energy costs over a reasonable domain. The impact of energy costs is modelled with the equations representing the macroeconomy (Eqs. (6-1)-(6-4)), which determine the actual (as opposed to the reference) economic growth trajectory, and price-induced substitution between the energy and capital-labour bundles, and within the energy bundle.

6.2.2.4 The energy cost function

In order for the production function and macroeconomic model described above to optimise, it requires energy and transport cost information. This is determined by ERIS, but because ERIS contains a high level of energy system detail (with around 65,000 equations), including non-linear technology learning curves, it is not practical to integrate ERIS directly into the macroeconomic model.[62] However, the macroeconomic model still requires a cost function (i.e., supply curve) containing information from ERIS. This leads to the same problem discussed by Messner and Schrattenholzer (2000), that defining the energy cost function implied by ERIS would require an ERIS run for each possible point along the supply curve. Considering the number of possible demand configurations across 11 world regions over the century, this is not feasible.

However, as discussed in Messner and Schrattenholzer (2000), it is possible to use a simulated cost function that reproduces the supply curve implicit in ERIS at the optimal point (specifically, the value and gradient of the supply curve). Accordingly, the ERIS energy cost curve is simulated in the macroeconomic model as a cubic function of demand of the form:

$$EC_t = A_t + \sum_j c_{j,t} \bullet energy_{j,t}^{\,3} \qquad (6\text{-}5)$$

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[61] Specifically, UDFs are parameterised such that under the reference scenario for economic activity, energy demand and prices, the following is maintained for all *t*:

$$\frac{\partial U}{\partial I_t} = 0, \text{ which is equivalent to } \frac{\partial U}{\partial C_t} = 0$$

Failure to calibrate *UDF*s on this basis means that an alternative investment (and hence economic growth) pathway is more optimal under reference prices, and the reference scenario is not reproduced.

[62] Note, this approach is used in the MERGE model, which has a relatively less detailed representation of the energy system (Manne *et al.* 1995).

where the parameters A_t and $c_{j,t}$ are determined according to energy price and energy cost (EC_t) outputs from ERIS.[63] How this function and the macroeconomic model are linked is discussed in more detail in Section 6.2.4 below.

6.2.3 The passenger transport model

As mentioned above, the energy (and transport) inputs to the ECLIPSE production function comprise electric, non-electric and heat energy and freight transport. It is assumed that passenger transport is not an input to the production function, but is instead demanded primarily by final consumers. Accordingly, energy used in passenger transport is modelled using a different approach, and in a way consistent with the scenario development in Section 3.2.2 (Chapter 3). Specifically, passenger transport energy demand is determined directly by the ERIS model from inputs of demand for energy service (passenger-km) based on the work of Schafer and Victor (2000). In Schafer and Victor's (2000) model demand for passenger transportation is determined by consumer money and time budgets, and the price and speed of different transport modes. This approach is also applied here to develop a separate passenger transport demand model for determining inputs to the ERIS component of ECLIPSE. However, once again it is important to emphasise that this transport model is not used to project future transport demand, but is instead used to examine how a scenario of future transport demand,[64] consistent with other scenario features, responds to changes in energy prices.

Accordingly, similarly to the macroeconomic model discussed above, the passenger transport model is calibrated using the scenario presented in Section 3.2.2, from which consumer travel budgets and the share of income devoted to private motor vehicle (PMV) and passenger air travel in each time period (and in each region) are calculated. These travel money budget shares of income (TMBS) are then assumed to remain constant, and are calculated as follows for each world region:

$$TMBS_t = \frac{\sum_{\text{mode}} \frac{pkm^*_{\text{mode},t}}{Pop_t} \bullet p^*_{\text{mode},t}}{\frac{GDP^*_t}{Pop_t}} \qquad (6\text{-}6)$$

where $p^*_{mode,t}$ is the cost per passenger-km of each transport mode in each time period, and $pkm^*_{mode,t}$ is the total passenger-km travel for each mode in each time period under the reference scenario. Passenger travel costs ($p^*_{mode,t}$) are obtained from ERIS.[65]

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[63] That is, given that the energy price ($p^*_{j,t}$) from ERIS is equal to the derivative of the energy cost function (Eq. (6-5)) for a given energy demand:

$$p^*_{j,t} = \frac{\partial EC}{\partial energy_j} = 3 \bullet c_{j,t} \bullet energy_{j,t}^{\ 2}$$

$$\therefore c_{j,t} = \frac{p^*_{j,t}}{3 \bullet energy_{j,t}^{\ 2}}$$

[64] Such as that developed by Turton and Barreto (2005) and presented in Section 3.2.2.

[65] Car travel costs from ERIS are estimated on a vehicle-km basis and include only fuel costs, so are converted to a p-km basis by including a maintenance and balance of vehicle component (*BOV*), and incorporating occupancy projections:

The scenario of future transport demand is also used to estimate world regional travel time budgets (*TTB*), which are assumed to be independent of changes in other variables (such as travel price and incomes), based on the work of Schafer and Victor (2000) and Zahavi and Talvitie (1980). Time budgets are estimated as follows:[66]

$$TTB_t = \sum_{\text{mode}} pkm^*_{\text{mode},t} \Big/ Speed_{\text{mode},t} \qquad (6\text{-}7)$$

The TMBS and the TTB are then used as the basis for analysing the impact on transport of alternative policies or market developments. Specifically, during each iteration step, the ERIS model determines the price of PMV and air passenger transport ($p_{mode,t}$) on a per p-km basis. The transport model then determines the optimal mix of PMV and air transport using these prices and the fixed time and money budgets:[67]

$$TMBS_t \bullet \frac{GDP_t}{POP_t} \geqslant \sum_{\text{mode}} \frac{pkm_{\text{mode},t}}{POP_t} \bullet p_{\text{mode},t} \qquad (6\text{-}8)$$

$$TTB_t \geqslant \sum_{\text{mode}} pkm_{\text{mode},t} \Big/ Speed_{\text{mode},t} \qquad (6\text{-}9)$$

To solve the transport model it is assumed that the utility of travel exceeds the utility of consumption of other products or saving up to the travel money budget constraint, and that the utility of additional travel exceeds the utility of additional time up to the time budget constraint. Accordingly, the transport model determines travel demand by maximising total travel subject to the two inequalities given in Eqs. (6-8) and (6-9) above.

It is worth noting that this approach appears to imply quite a high long-run price elasticity of car utilisation. For example, under a fixed money budget, a 1 percent increase in the total price of car travel implies around a 1 percent decrease in demand, or even greater depending on the shift to other modes of transportation.[68] This implies an elasticity of -1 for total car travel with respect to total travel costs. However, it must be considered that a 1 percent increase in the price of fuel implies probably around only a 0.2-0.3 percent increase in the cost of car transport because fuel only accounts for a fraction of total travel costs (for

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$$p_{carpkm,t} = (p^*_{carkm,t} + BOV) \Big/ Occupancy_t$$

Air travel costs from ERIS are estimated based on fuel costs, and are converted to a per passenger-km basis using efficiency projections (*Eff*) and assumptions regarding the fuel cost share (*FCS*):

$$p_{airpkm,t} = (p^*_{air,t} \bullet Eff_t) \Big/ FCS_t$$

The *FCS* is calculated based on the observation that today fuel costs (including taxes and margins) represent 10-15 percent of operating costs of major airlines (e.g., see UAL (2004) and British Airways (2004)). These shares are applied for North America, with the shares in other regions determined according to relative efficiency. Airline fuel efficiency is projected to improve over time, as discussed in Section 3.2.2.

[66] The apparent time budget is determined on the basis that, on average, high-speed modes are 3 times faster than PMV transport. This assumption is designed to reflect the average relative speed based on the traveller's perspective. That is, although commercial aircraft are generally more than 3 times faster than cars, a significant amount of additional time is required to access commercial air travel (such as transport to and from ultimate origin and destination to airports, time for checking in and out, boarding/disembarking etc.).

[67] Although the money budget share of income remains constant in each iteration, changes in income result in a different money budget.

[68] Air transport generally has a higher cost per passenger-kilometre of travel, so based on fixed travel money budgets this implies a slightly higher price elasticity than for car travel.

example, see Turton and Barreto (2005), and IEA (2003f) to account for the difference between price and cost of fuel). The implied long-run elasticity of vehicle travel of around -0.25 with respect to fuel price is in line with estimates in the literature (for example, see Johansson and Schipper 1997).

6.2.4 Linking the model components

The previous sections have dealt with the definition of the macroeconomic output and transport models that determine energy and transport demand. This section describes how these models are used in conjunction with the ERIS model and scenario inputs (such as those presented in Section 3.2, but more generally from the Scenario Generator—see Nakićenović *et al.* 1998) to estimate energy system and economic characteristics, thereby describing the overall operation of the integrated policy analysis tool. As discussed in Section 6.2.2.4, it is a requirement that the energy cost function simulates the detailed supply function of ERIS about the optimal point. To ensure that the point determined by the model (based on energy demands and prices) is optimal ECLIPSE iterates between ERIS and the macroeconomic and transport models until energy demands and energy prices converge to close to identical values in all models.

The overall modelling framework is presented schematically in Figure 6-2 and described below. In Figure 6-2, the dotted lines from the Scenario Generator represent once-only inputs, whereas the lines between the macroeconomic, ERIS and transport models (unbroken and dashed) represent iteration loops within ECLIPSE. The actual operation of the linked models, including calibration steps, is described below.

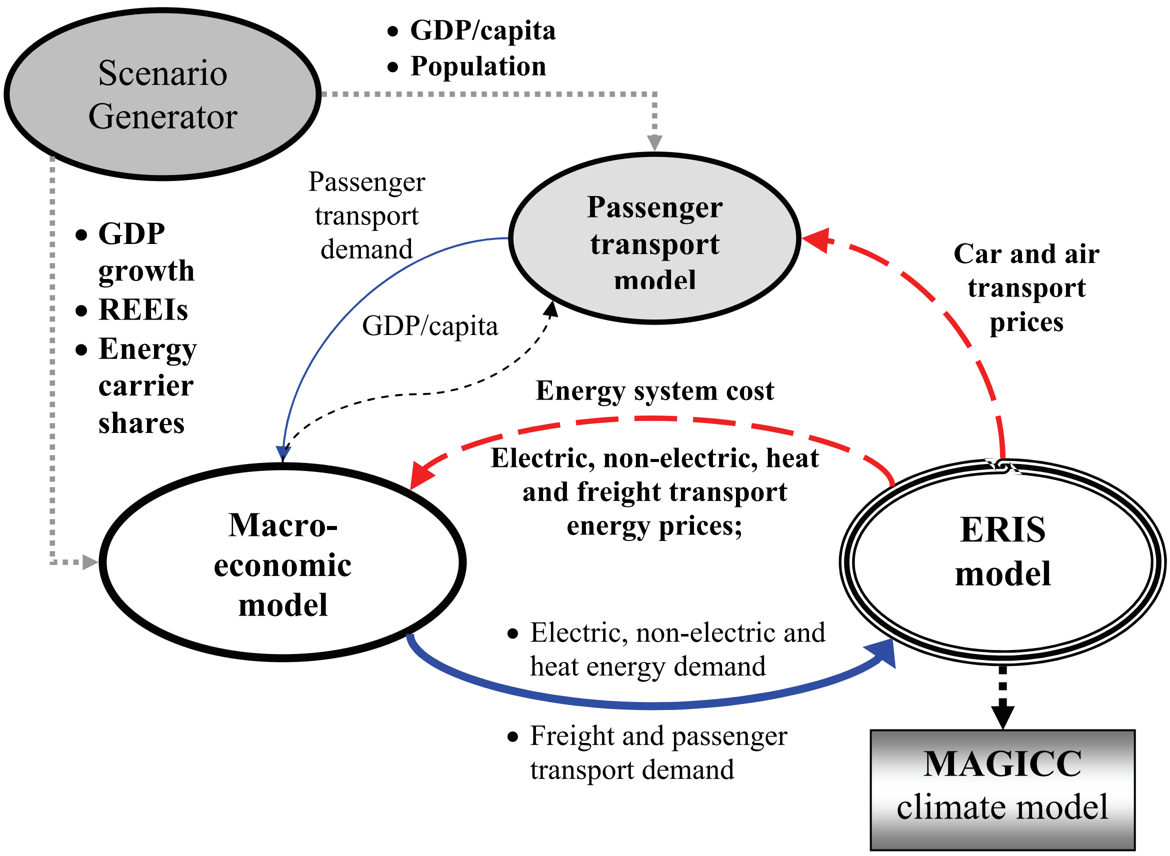

Figure 6-2 ECLIPSE model framework and operation

6.2.4.1 Iterating between the models

Before commencing the iteration process, the macroeconomic model is first calibrated using inputs from the Scenario Generator (see Section 6.2.2.3, based in this case on the scenario described in Section 3.2) and output from an initial solution of the ERIS model. This initial solution is based on actual 2000 energy demands and an initial projection of future energy demands based on a reference demand path—that is, the path implied by the reference economic growth rate and REEIs (see Section 6.2.2.3). A reference transport energy demand projection is also estimated and used in the initial ERIS solution, based on the methodology described in Schafer and Victor (2000) and modified by Turton and Barreto (2005), to which we return in Section 6.3 below.

One of the key sets of calibration parameters applied to the macroeconomic model is the reference energy price path. Reference energy prices are the prices under which the macroeconomic model will reproduce the reference demands and economic growth rates defined by the combination of population growth, economic activity and energy intensity (presented for the B2 scenario in Figure 3-2, Figure 3-3 and Figure 3-5, respectively). These reference prices are estimated guided by scenario parameters and output from ERIS—the specific reference price assumptions used here are presented in Section 6.3 below. After calibration, all the parameters are fixed and the models are solved iteratively, according to the following steps:

1. The transport model and then the macroeconomic model are solved for each of the 11 world regions separately on the basis that regions seek to maximise their own aggregate utility. This approach requires that information on energy trade is also input from ERIS, and the macroeconomic model then determines trade in other goods and services on the basis that regions maintain a balanced trade account.

2. The energy demanded by the economy and passenger transport is then fed back into ERIS, which estimates energy price and other energy system characteristics.

Steps 1 and 2 are repeated until the solution converges to a satisfactory tolerance level. However, it is important to ensure that simulating the energy supply cost curve (as discussed in Section 6.2.2.4) does not restrict the ability of the model to converge. This is discussed below.

6.2.4.2 Dealing with model over-response

Simulating the ERIS supply curve with a simple cubic equation as described in Section 6.2.2.4 greatly simplifies a complex energy system, but may also give rise to a number of complications. The ERIS energy supply curve is not expected to be smooth, and may have discontinuities. This occurs because competing technologies and fuels in ERIS have different costs, and there are limits on the amount of final energy that a particular technology or fuel can provide. These limits are dynamic (such as maximum technology deployment and diffusion rates) and static (such as the total availability of primary fuels). Accordingly, when one technology or resource category is fully utilised, the marginal cost of an additional unit of energy production will reflect the cost of the next cheapest technology or fuel resource, which may be significantly higher than the cost of the fully-utilised technology. Some of these limits are described in more detail in Turton and Barreto (2004) and Kypreos *et al.* (2000).

As a consequence, the change in marginal energy price resulting from even a very small change in demand for energy may be large, which may lead to problems of convergence if the cost function approximation used in the macroeconomic model is inconsistent with the cost function implicit in ERIS. This is illustrated in the left panel of Figure 6-3, which shows an example demand curve from the macroeconomic model and an example of an extreme supply curve from ERIS, and some illustrative simulated supply curves across several iterations. Because part of the example ERIS cost function is substantially steeper than the simulated cost functions, the demands determined by the macroeconomic model may change too rapidly across iterations, leading to oscillations between two demand levels. This is shown by the dashed line in the right panel of Figure 6-3, which represents the apparent supply-demand balance based on the simulated cost curves shown in the left panel. This dashed line never completely converges to the optimal market-clearing demand.

There are two ways to avoid this problem: i) ensure that the supply (cost) function used in the macroeconomic module is steeper than the ERIS supply function about a point of oscillation; or ii) limit the size of any oscillation such that the macroeconomic model moves slowly towards the point of convergence rather than jumping from side to side. Experience with the iteration process has shown that the ERIS cost function is extremely steep about certain demand levels, such that formulating a sufficiently steep cost function in the macroeconomic module results in key solver tolerances being exceeded. Accordingly, we have opted to progressively limit the demand response of the macroeconomic model whenever demand is oscillating. That is, where demand is oscillating between two levels, it is assumed that the optimal demand level lies between these two values, and the allowable change in demand is reduced for the next iteration. To avoid artificial convergence, the allowable range of demands is not limited, only the amount by which demand can change from one iteration to the next—and only where demands are oscillating. The unbroken line shown in the right panel of Figure 6-3 illustrates the impact of these restrictions on demand across several iterations. In this case, demand converges suitably and the market clears.

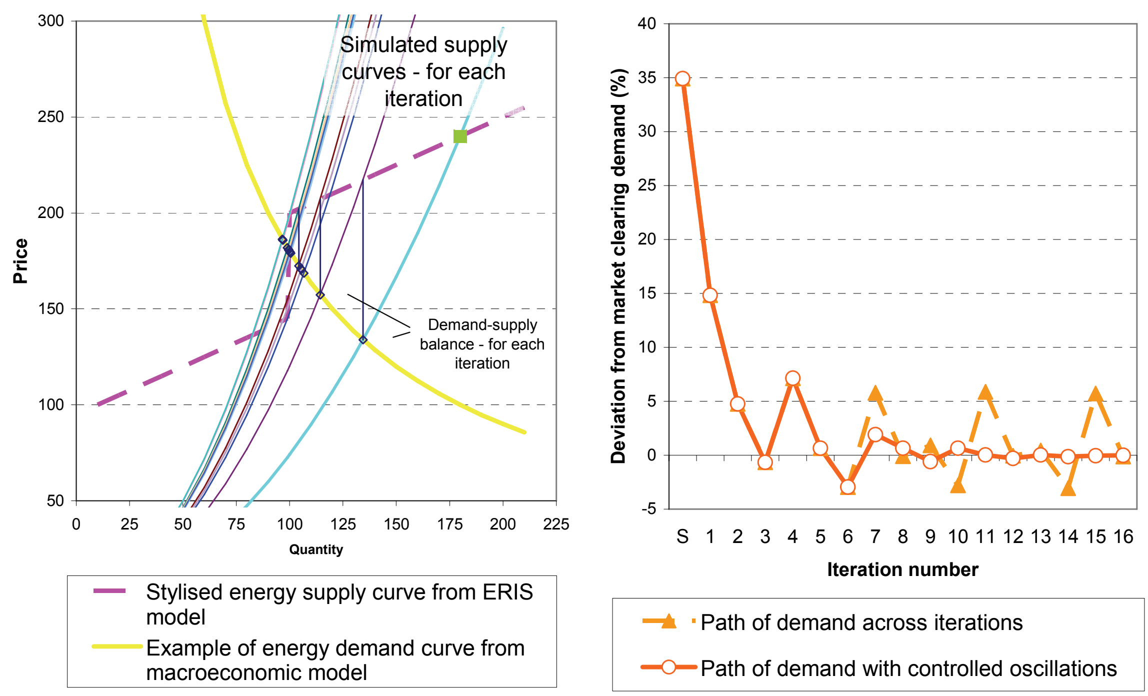

Figure 6-3 Illustration of supply-demand balance, model over-response

This completes the description of the main features of the integrated ECLIPSE model, although some additional aspects are discussed in the following section. We now look at some results of this modelling framework.

6.3 Results and discussion

To illustrate how the ECLIPSE model described in this chapter operates in practice, and represents an improvement compared to some other approaches, this section presents a number of results illustrating different model features. These results are based on a B2-SRES[69] scenario (Nakićenović and Swart 2000; Riahi and Roehrl 2000), which is used to define reference growth rates and REEIs under reference prices (see Figure 3-5 in Chapter 3 for details on reference energy efficiency assumptions), although we updated the scenario with economic output data for 2000 (Miketa 2004). As mentioned earlier, B2 is a "dynamics-as-usual" scenario, where differences in economic growth across world regions are gradually reduced and concerns for environmental and social sustainability at the local and regional levels rise gradually along the time horizon. The reference price scenario applied for this analysis is presented in Figure 6-4, which also shows historical oil prices (BP 2005). It should be noted that the reference energy price path is not designed to represent the oil price, but is instead an indicator of aggregate energy cost. Finally, the transport model was calibrated with the scenario from Turton and Barreto (2005), which was developed with a modified version of the Schafer and Victor model (2000).[70]

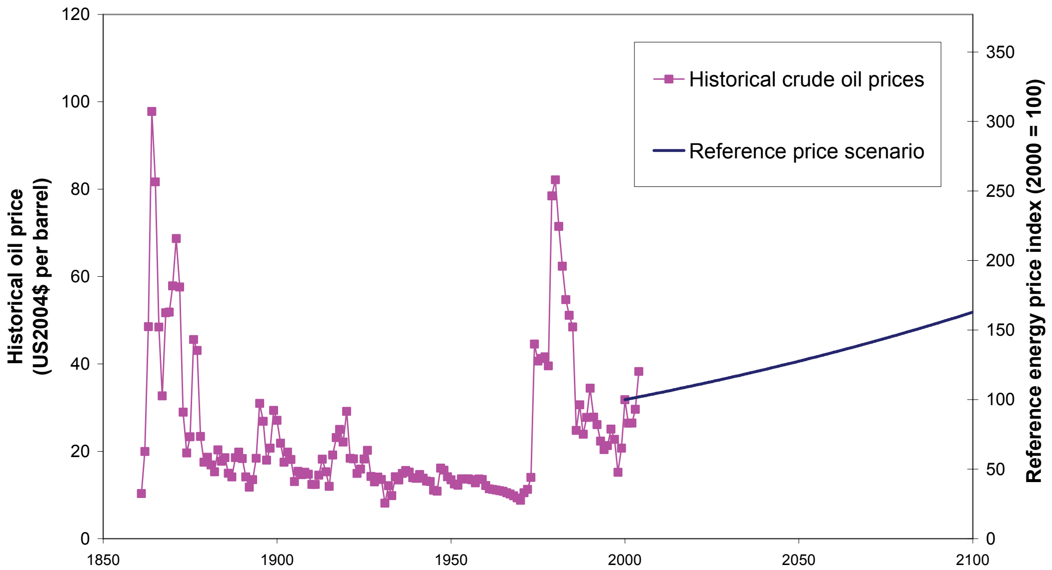

Figure 6-4 Historical crude oil prices and assumed reference energy prices

Note: Historical data sourced from BP 2005.

[69] Special Report on Emissions Scenarios (Nakicenovic and Swart 2000).

[70] Schafer and Victor's (2000) model was originally applied to estimate total demand for passenger travel, shares of various modes and vehicle occupancy rates to 2050 for the IS92a/e scenarios (Leggett *et al.* 1992). However, the B2 scenario applied here differs considerably from the IS92a/e scenarios in terms of population and economic growth, and because of a considerably longer timeframe in B2 (to 2100 rather than 2050). Accordingly, as discussed in Section 3.2.2.1 in Chapter 3 it was necessary to extrapolate and modify some of the model regression equations used by Schafer and Victor (2000), taking into account realistic trends in vehicle ownership, the share of various modes and likely occupancy and utilisation levels.

The ERIS model was run in either linear (LP) or mixed integer (MIP) mode for each iteration (see Section 3.3 in Chapter 3), with technology learning dynamics included either endogenously (MIP) or exogenously (LP, based on MIP learning parameters, but using installed capacities from previous iteration). In general, the LP version of ERIS was used for initial calibration, and the MIP version for generating final results. The first part of this section presents a series of results that illustrate how the model converges with consecutive iterations.

6.3.1 Operation of the hybrid model

As discussed in Section 6.2.4.1, the hybrid model is solved by iterating energy demands into ERIS, which determines the energy shadow prices that are then fed into the macroeconomic model, which determines new demands. This process is repeated until convergence criteria are satisfied. Figure 6-5 shows how, with each iteration, global electricity demand progressively converges under a baseline scenario (Figure 6-5 presents the percentage deviation from the convergence point). Energy system and macroeconomic features determine the pace and character of the convergence. However, it should be noted that even when aggregate reference demands are relatively close to aggregate demands at convergence (as in Figure 6-5), this hides the fact that regional reference demands diverge significantly more. For example, Figure 6-6 presents iteration results for sub-Saharan Africa, where reference demands range +/-20 percent from convergence demands, partly explaining the apparently slow convergence in aggregate global demand (in Figure 6-5).

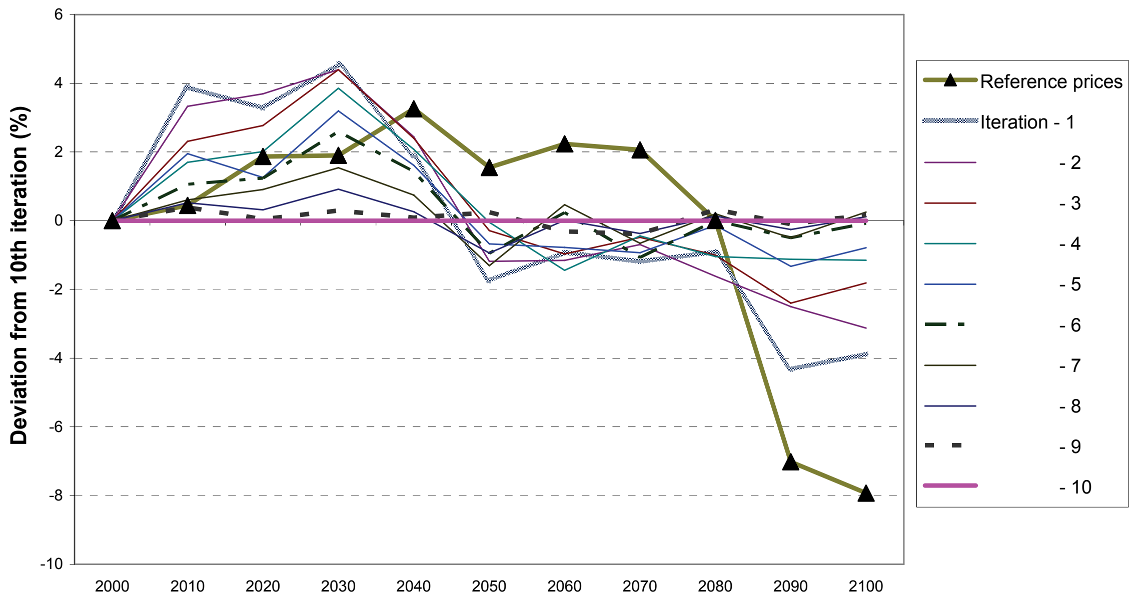

Figure 6-5 Convergence of global electricity demand, baseline scenario

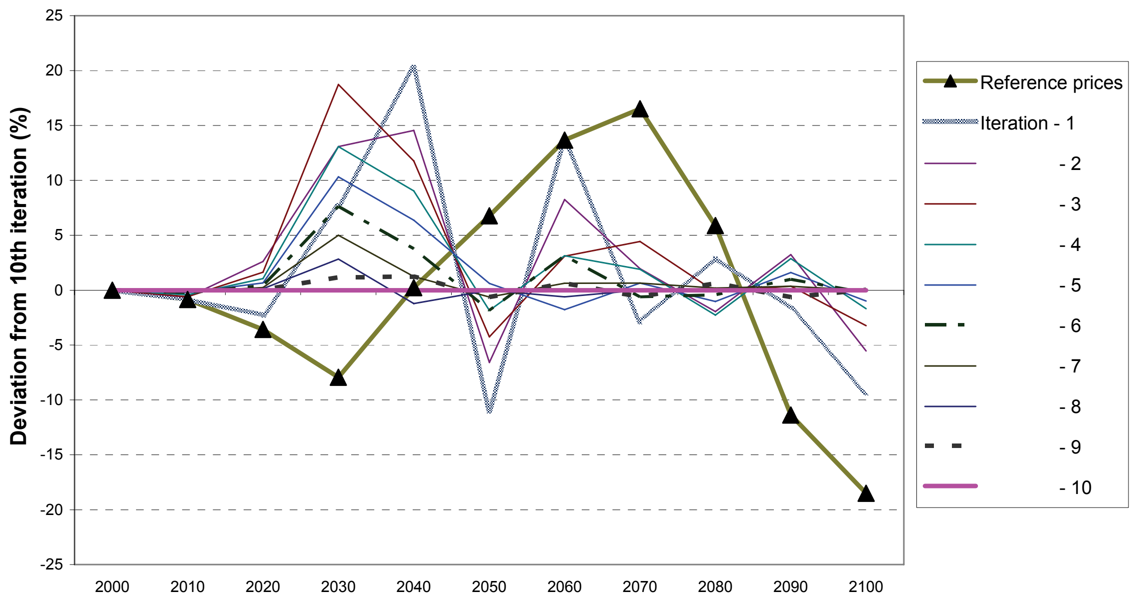

Figure 6-6 Convergence of sub-Saharan Africa (AFR) electricity demand, baseline scenario

Another key variable of interest is economic activity, and Figure 6-7 presents the convergence of global GDP under this B2 baseline scenario. Between as early as the fourth iteration and the 10th, GDP levels vary by less than 0.1 percent across iterations. However, this rapid convergence is not surprising when one considers that energy costs account for only a small proportion of global GDP, although energy costs also converge.

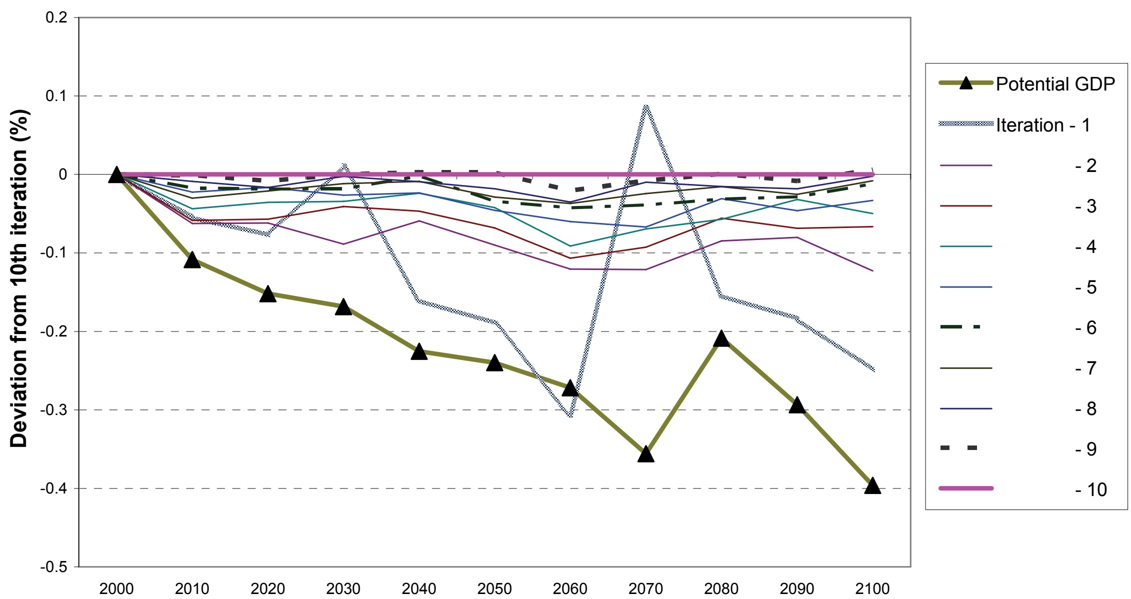

Figure 6-7 Convergence of global GDP, baseline scenario

A similar result is seen in Figure 6-8 for car transport demand, where it is only necessary to present the first five iterations before demand effectively converges. As discussed in Section 6.2.3, these demands are calculated based on travel money and time budgets, an approach that incorporates the relatively inelastic nature of passenger transport demand. This partly reflects the fact that energy costs (after excluding taxes and margins) are a relatively small part of total passenger transport costs.

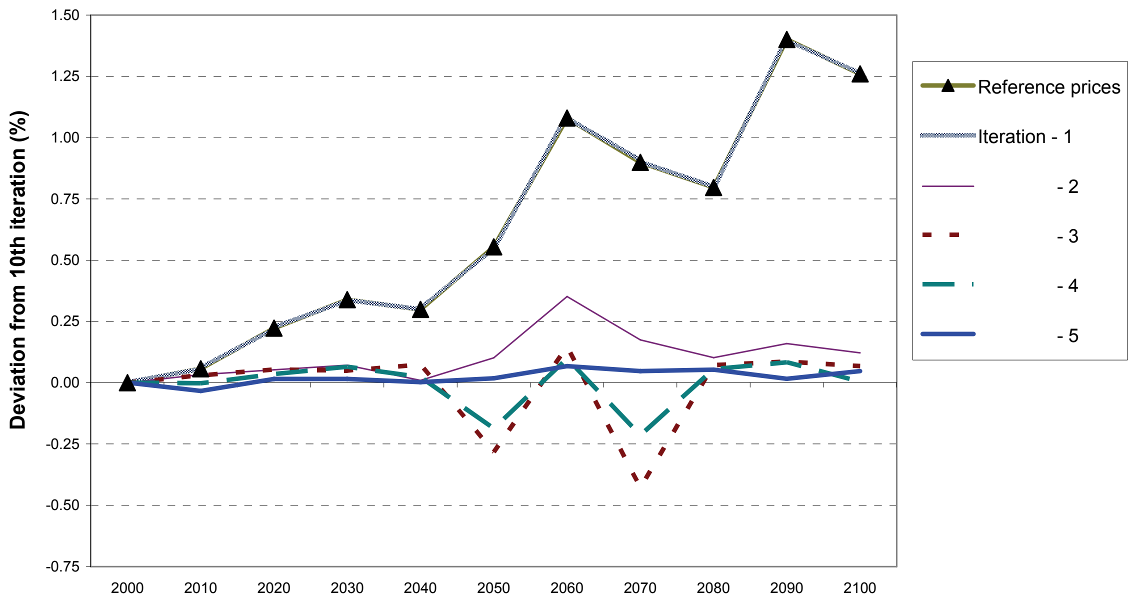

Figure 6-8 Global car transport demand and convergence, baseline scenario

These results illustrate the technical operation of the iteration process and the convergence of demands and economic output. The next part of this section presents some results illustrating some of the new calibration features of ECLIPSE.

6.3.2 New model features and calibration

A key objective of the model presented in this chapter is to examine the impact of market conditions or policy measures on economic growth and energy demand. As described earlier, however, ECLIPSE can not be used to model economic growth *per se*, but is instead suitable for exploring the impact of alternative policy or market scenarios on an exogenous reference scenario of economic growth.

In order to be able to interpret meaningfully the results of alternative policy or market scenarios, it is important that the ECLIPSE macroeconomic model be able to reproduce the reference scenario under hypothetical reference prices. As discussed in Sections 6.2.2.3 and 6.2.2.2, two features (among others) in the ECLIPSE macroeconomic model contribute to realising this objective. The first feature, which we return to later, relates to the consistency in the parameterisation and application of the model, whereas the second is the calibration of the utility discount factors (UDFs).

6.3.2.1 Utility discount factor calibration

The UDFs in ECLIPSE and other models (Messner and Schrattenholzer 2000; Kypreos 1996; Manne *et al.* 1995) determine preferences for consumption *versus* investment. Since these UDFs represent the preference between present and future consumption, they are affected by the marginal future utility of investment, which itself is affected by the marginal product of capital (MPC). The parameterisation of MPCs in ECLIPSE represents an important deviation from the approaches adopted in MESSAGE-MACRO, MERGE and MARKAL-MACRO.

To illustrate how the choice of MPCs in ECLIPSE affects the ability of the model to reproduce the reference economic growth trajectory under reference prices, we show in Figure 6-9 the deviation from the reference growth rate when different MPCs are applied. In this figure, the line labelled 'ECLIPSE' shows the deviation when the UDFs are set on the basis of the MPCs implied by the production function under the reference energy path. In this case the deviation from reference growth is negligible, and the only reason there is any deviation is because constraints in the ERIS component of ECLIPSE restrict energy technology deployment to a rate below that required to achieve reference energy demands for two world regions in two periods—South Asia (2010) and sub-Saharan Africa (2060)—with some catch-up in subsequent years.[71]

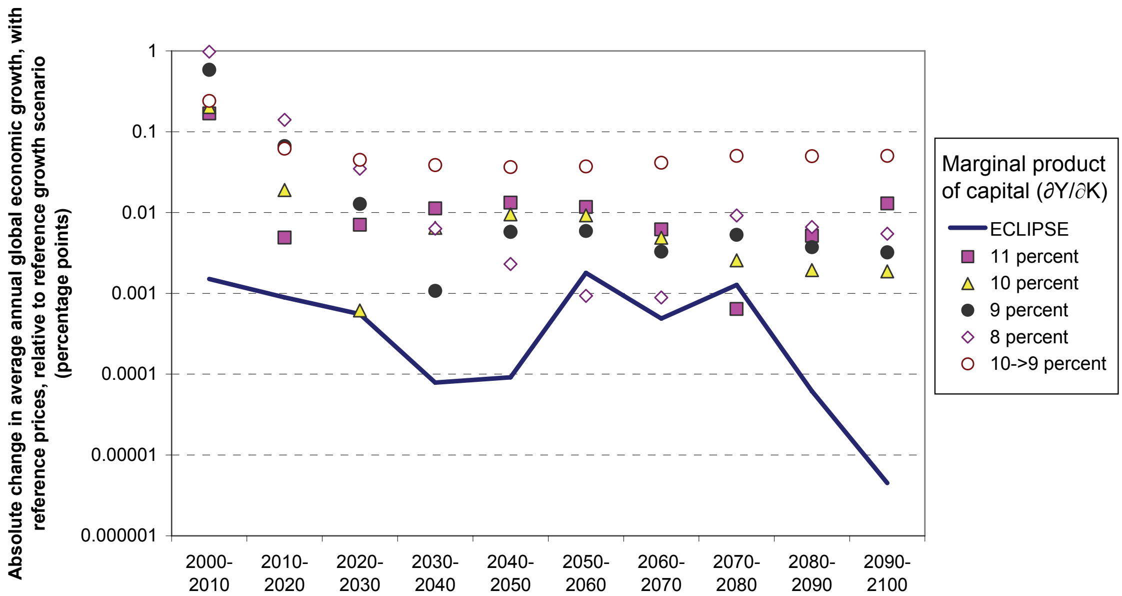

Figure 6-9 Impact of alternative marginal production of capital (and UDF) assumptions on average global economic growth, under reference prices

This figure also shows the impact of applying alternative MPCs.[72] This provides an indication of how the calibration of ECLIPSE differs from some of the other models mentioned earlier (Messner and Schrattenholzer 2000; Kypreos 1996; Manne *et al.* 1995) which apply MPCs

[71] This may highlight a case for revisiting technology deployment constraints in ERIS, but on the other hand it helps illustrate that under this reference scenario the speed at which energy infrastructure can develop will potentially limit rate of economic growth achievable in rapidly developing regions.

[72] Noting that the average MPC in ECLIPSE is around 10.4 percent, with a standard deviation of 0.4 percentage points. MESSAGE-MACRO uses UDFs defined with MPCs around 10 percent, while MERGE applies MPCs over a similar period between 10 and 9 percent.

that are defined independently of the MPC implied by their respective production functions. Figure 6-9 shows that these alternative MPCs result in a larger deviation in average annual growth than observed with the well-calibrated ECLIPSE model. The largest divergence, which occurs in the first period, is in some cases highly significant compared to the global average annual growth rate in the reference scenario presented here (around 3 percent).

These results show that using MPCs that are inconsistent with those implied by the production function can result in a poorly calibrated model that is unable to reproduce the reference scenario (used in calibration) under reference prices. That is, such a model starts with a baseline that deviates significantly from the reference scenario, running the risk of over- or underestimating impacts of alternative policy or market scenarios. In comparison, ECLIPSE is significantly better calibrated, and therefore more likely to behave in a robust way. Importantly, however, it should be noted that we have only shown how ECLIPSE behaves with the MPCs similar to those used in some of the other models discussed (Messner and Schrattenholzer 2000; Kypreos 1996; Manne *et al.* 1995), as distinct from showing how these other models themselves behave.

6.3.2.2 Consistency in calibration and application

The other requirement mentioned above for ensuring that the macroeconomic model is able to generate meaningful results, is that the production function is calibrated and applied in a consistent way; and here we focus on this consistency with respect to energy efficiency improvements, as discussed in Section 6.2.2.2. In the ECLIPSE production function a consistent approach is used because the average energy intensity of all vintages of capital and labour, as represented in the reference scenario, is used to set parameters that are also applied to all vintages during model runs. However, as mentioned in Section 6.2.2.2, this is also an area where ECLIPSE differs significantly from some other approaches, which we explore in Figure 6-10.

Figure 6-10 shows the percentage deviation from the reference scenario of global electricity demand estimated by the macroeconomic model under reference prices, for three alternative calibration–application approaches. The line labelled “avg. cal + avg. app.” illustrates the results generated with the approach used in ECLIPSE. These results show that ECLIPSE matches closely the reference demand scenario—with the slight deviation explained by the constraints in ERIS discussed above in Section 6.3.2.1.

For comparison, Figure 6-10 also shows the percentage deviation from the reference global electricity demands if we instead apply in the ECLIPSE macroeconomic model the alternative approach cited in Section 6.2.2.2 and applied in some of the other models, such as MERGE (Manne *et al.* 1995; Manne and Richels 2004). Specifically, in MERGE some parameters in the production function are calibrated using the *average* energy intensity of all vintages of capital and labour, but the model is then applied in each period to estimate energy demand of *new* vintages only. The impact on electricity demands of applying his approach in ECLIPSE under reference prices is illustrated by the line labelled “avg. cal + new app”. As postulated in Section 6.2.2.2, the results in Figure 6-10 show that this approach underestimates the impact of energy intensity improvements relative to the reference scenario used to calibrate the model.

Figure 6-10 Impact on global electricity demand of alternative approaches to calibration and application of the ECLIPSE macroeconomic model, under reference prices

To maintain consistency with the reference scenario using this approach it is necessary to calibrate the production function on the basis of the energy intensity of new vintages. The impact of this alternative approach on global electricity demand under reference prices, is shown by the line labelled "new. cal + new app" in Figure 6-10. This line is almost identical to the reference energy demands (and also the "avg. cal + avg. app" line).

These results illustrate the impact of alternative approaches to model calibration and application, and show how an inconsistent approach leads to significant deviations in model output. Moreover, the results show that ECLIPSE achieves consistency in the treatment of energy intensity improvements.

Having illustrated two features of the improved calibration of the ECLIPSE model, the following section compares the results of applying the ECLIPSE modelling framework with those produced with the stand-alone ERIS model. This illustrates some of the additional insights afforded by using a modelling framework which combines top-down and bottom-up responses.

6.3.3 Comparison of the hybrid ECLIPSE model with the bottom-up ERIS model

As outlined in Section 6.1, the purpose of linking top-down and bottom-up models—the main focus of this chapter—is to overcome some of the limitations of applying these modelling approaches independently. In the case of bottom-up models, one critical limitation is that the interactions between economic forces and energy demand, including the impacts of energy prices on energy demand, are not well represented.

This limitation is partly overcome in the ECLIPSE model, and to illustrate some of the effects this has on model output, we now compare the results from ECLIPSE with those generated using the stand-alone bottom-up ERIS model, with otherwise identical scenario inputs. For this comparison it is important to note that the set of modelling outputs generated by both ERIS and ECLIPSE is relatively limited, given that ERIS is an engineering-based model that does not include any representation of macroeconomic features. Nonetheless, in addition to changes in demand arising from the incorporation of the price response in ECLIPSE, we can also compare how changes in demand in turn affect technology and fuel choice.

For instance, Figure 6-11 presents the difference between the output of the ECLIPSE and ERIS-only models for global electricity generation under a baseline scenario.[73] The first feature worth noting in Figure 6-11 is that the total electricity generation estimated with the ECLIPSE model is substantially lower (almost as much as 20 percent lower than with the stand-alone ERIS by 2100), because of the ability of ECLIPSE to respond to changes in energy prices by, in this case, reducing demand. Moreover, this reduced demand affects the combination of technologies and fuels used under this baseline scenario compared to the ERIS-only case. Figure 6-11 shows that although generation is lower from all sources, the largest relative reductions appear to be for oil, biomass and renewable generation.

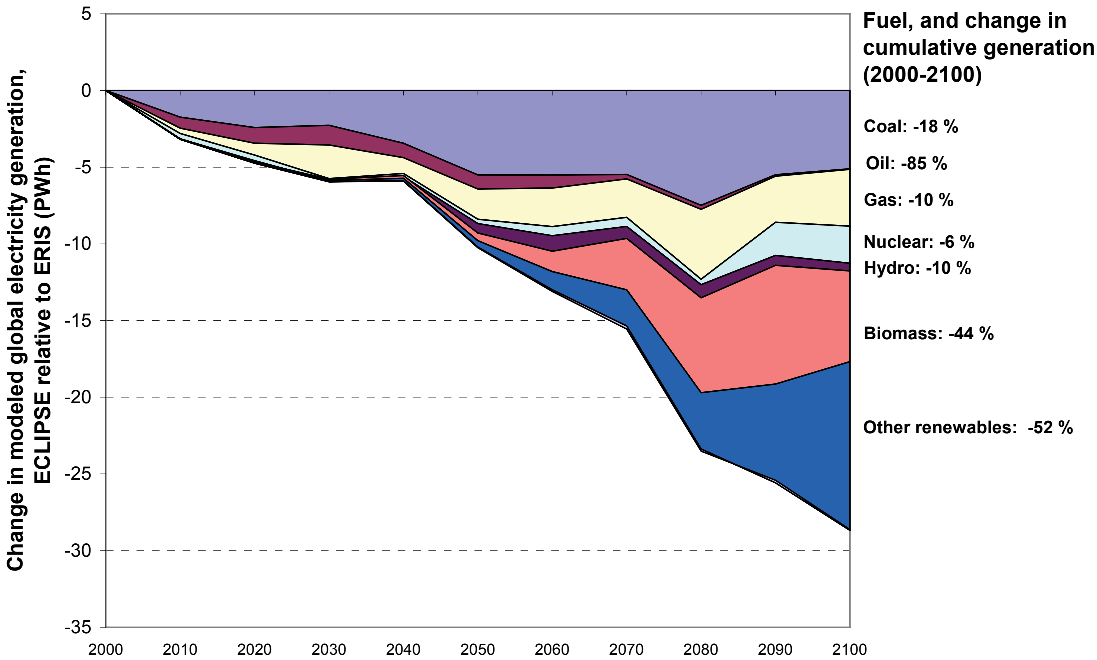

Figure 6-11 Comparison of electricity generation with ECLIPSE and ERIS, baseline scenario

Given the cost-minimising and utility-maximising behaviour of ECLIPSE, this result arises because these generation technologies are relatively expensive. That is, ECLIPSE is able to represent preferences for reduced energy consumption over deployment of expensive technologies, which ERIS is unable to do. Importantly, however, one should recognise that these results depend on the reference price scenario used to calibrate the ECLIPSE model. While the reference scenario presented in Figure 6-4 at the start of Section 6.3 appears very reasonable in the context of the SRES B2 scenario, given historical developments, an

[73] Note, this is different from the reference scenario referred to throughout this chapter, in that it includes the impact on demand of prices generated by the ERIS model.

alternative scenario with very high prices would generate different, and possibly contrary results to those presented above.

Similar results are exhibited in the transport sector, as illustrated in Figure 6-12 which shows the differences in demand for different transport fuels between ECLIPSE and ERIS for the same baseline scenario. Figure 6-12 shows that compared to ERIS, ECLIPSE estimates lower demand for all fuels except for natural gas—with petroleum and hydrogen consumption reduced the most. Natural gas consumption in transport is able to increase substantially relative to the ERIS-only case because of the reduced demand for this fuel in other sectors (such as electricity production—see Figure 6-11), arising from ECLIPSE's ability to substitute between energy and other inputs.

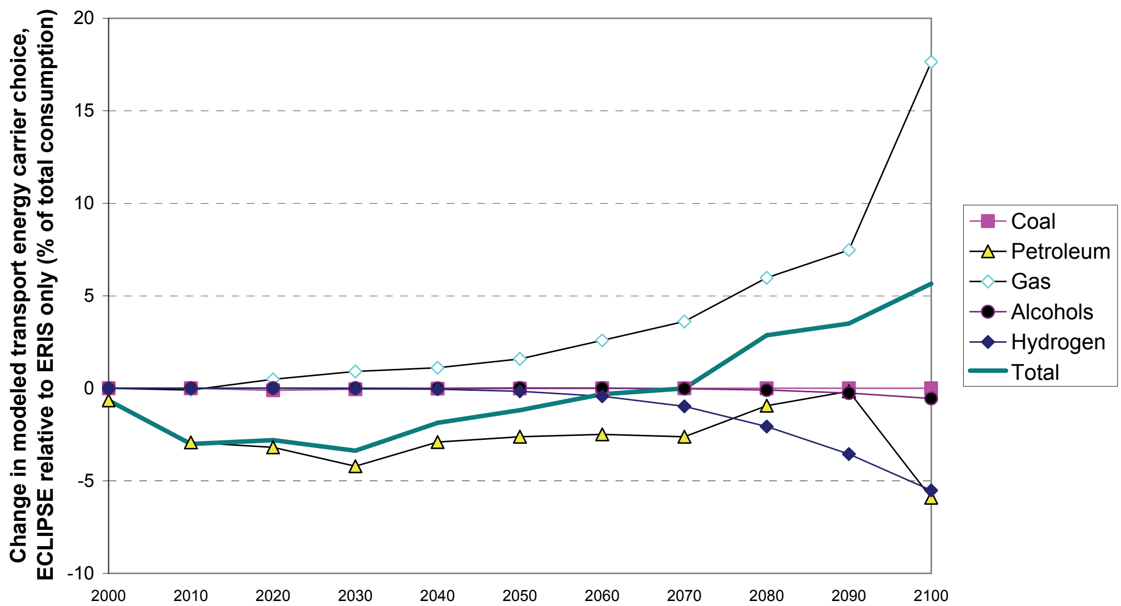

Figure 6-12 Comparison of transport fuel demand with ECLIPSE and ERIS, baseline scenario

This increased availability of natural gas for transport in ECLIPSE displaces around 75 percent of the cumulative hydrogen used in transport over the century (compared with ERIS), and around 3.5 percent of the cumulative petroleum consumption.[74] This reduced hydrogen demand coincides with reduced deployment of fuel cells, leading to lower overall energy efficiency and hence higher total transport energy demand relative to the ERIS-only case, as shown in Figure 6-12. Nonetheless, similar to the results for electricity generation, the results in Figure 6-12 indicate that more expensive fuels—such as hydrogen and unconventional oil—are avoided when the model used allows demand to respond to price changes.

To explore whether the effects discussed above are reasonably robust, a comparison between ECLIPSE and ERIS was made for a number of GHG abatement runs. Specifically, we examined the impact of achieving atmospheric CO_2 concentration targets of 750, 700 and 650 ppmv (compared to 780 and over 800 ppmv in the ECLIPSE and ERIS baselines, respectively) on the sets of technologies chosen by ECLIPSE and ERIS. Figure 6-13 shows the impact on cumulative electricity generation and transport fuel consumption (for different

[74] And around 86 percent of cumulative alcohol consumption in transport.

fuels) of using ECLIPSE *versus* ERIS. The results in Figure 6-13 concur with the findings from the baseline case, where deployment of more expensive (or less-mature) technologies and fuels is reduced when the price response in ECLIPSE is included. On the other hand, the reduced demand in certain sectors enables more of some fuels to be used in other sectors—for example, natural gas in transport, and biomass in electricity generation (under increasingly stringent concentration targets)—as shown in Figure 6-13.

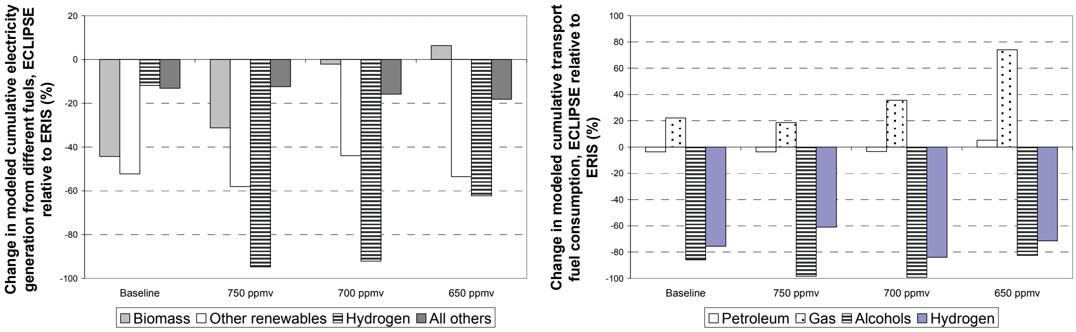

Figure 6-13 Comparison of electricity generation and transport fuel demand with ECLIPSE and ERIS, GHG abatement scenarios

The reduced deployment of new technologies implies that increased energy efficiency, rather than new supply-side technology options, may be much more important for supporting future economic and consumption activity than suggested by bottom-up energy system models, in which demand is inelastic to price. That is, conventional bottom-up energy system models may overestimate the deployment of new (and relatively expensive) technologies. Moreover, this is likely to have a cumulative effect because the performance, costs and competitiveness of many new technologies are likely to improve with market experience (via so-called 'learning-by-doing') (McDonald and Schrattenholzer 2001; Nakićenović 2002). In contrast, the results from ECLIPSE indicate that the price responsiveness of energy demand may reduce opportunities for experience and learning. Some examples are shown in Figure 6-14, which presents the change in cumulative installed capacity—a proxy for market experience—of selected learning components estimated with ECLIPSE relative to ERIS, under the baseline scenario presented in this section. Figure 6-14 shows that installations of some technology components—such as fuel cells and advanced wind turbines—are reduced substantially when ECLIPSE is used. This indicates that if, in response to the higher energy prices necessary for new technologies to penetrate the market, energy demand is reduced, then opportunities for experience and learning with new technologies will diminish, further reducing their competitiveness. Furthermore, reduced demand may limit the incidence and scope of niche markets for new technologies. Accordingly, the ECLIPSE model presented here may better represent technological lock-in affects arising from high initial cost barriers facing new alternative technologies.

Despite these findings, it should be noted that Figure 6-14 also indicates that some newer technologies—such as advanced nuclear generation—remain cost effective and are deployed even with the reduced demand. This suggests the divergence between new technologies that are successfully deployed and those that are unable to realise potential learning opportunities could be exacerbated by the impact of potential demand responses to higher energy prices.

To summarise, we have attempted in this section to present some of the differences in the results generated by the hybrid ECLIPSE model that combines top-down and bottom-up features, with the stand-alone bottom-up ERIS model. Despite the limited set of outputs for which a comparison is meaningful, it is possible to derive a number of interesting insights from the differences between price-elastic and -inelastic models, particularly in terms of technology deployment and learning-by-doing. These results show that linking top-down and bottom-up models not only improves representation of drivers of energy demand, but by doing so may provide additional insights in terms of technology dynamics.

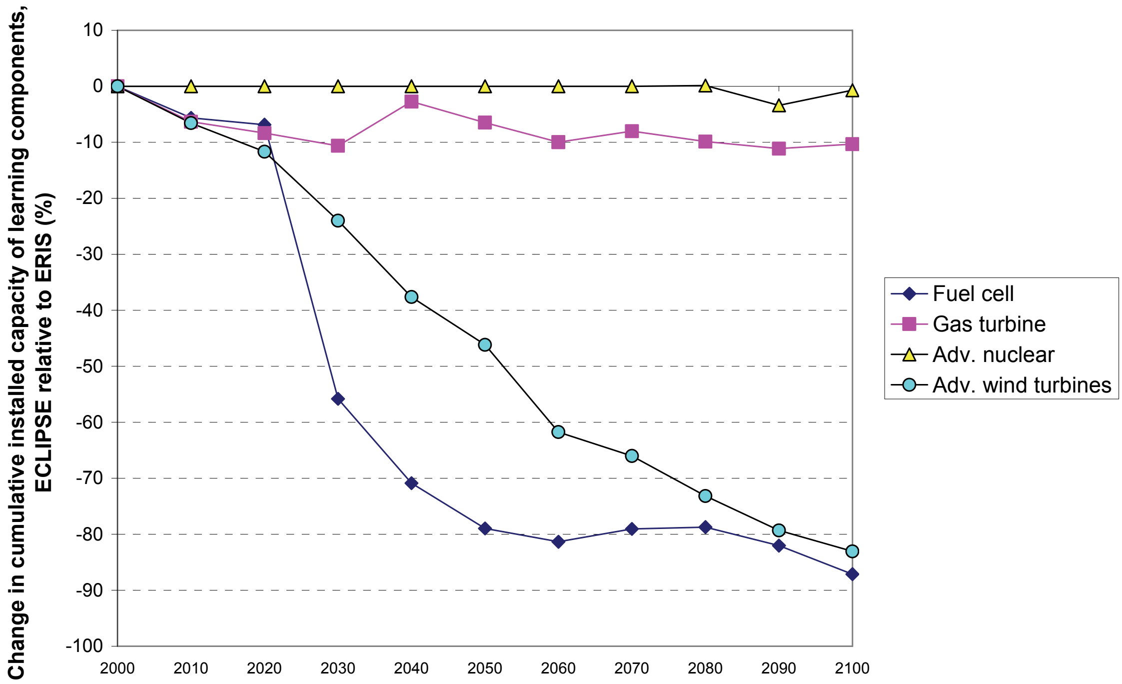

Figure 6-14 Comparison of cumulative installations of selected learning components with ECLIPSE and ERIS, baseline scenario

Having explored some of the differences between the bottom-up ERIS and the hybrid ECLIPSE models, we now turn to one important feature included in ECLIPSE, but not found in bottom-up-only models. We illustrate this feature—the ability to measure macroeconomic impacts—by applying the ECLIPSE modelling framework to a series of increasingly stringent GHG abatement policy cases. This exercise forms the basis for the more detailed analysis in Section 6.3.5 that addresses directly one objective outlined in Section 6.1 to develop a modelling tool suitable for examining climate change and other energy issues.

6.3.4 Impact on economic activity of a range of atmospheric CO_2 concentration targets

ECLIPSE was applied to model the global macroeconomic impact of a number of simple GHG mitigation policy scenarios, using the same B2-based economic growth and demand scenario described in Section 3.2 (Chapter 3). Specifically, aggregate GHG emissions targets were applied in ECLIPSE that were consistent with atmospheric CO_2 concentrations remaining below targets between 550 and 750 ppmv throughout the 21st century.

Although these targets relate specifically to CO_2 concentrations, equivalent constraints were applied to all of the three main GHGs based on global warming potentials. ECLIPSE was then solved to determine the 'when', 'where' and 'how' of GHG abatement. Compared to the stand-alone ERIS model which already includes a variety of abatement options for emissions of CO_2 and non-CO_2 gases, the modelling framework developed here includes additional ‘how’ abatement options such as substituting energy with capital, substituting between different types of energy and transport, and reducing economic activity.

The impact of these atmospheric concentration targets on global economic output is presented in Figure 6-15, showing in broad terms how the model responds across a range of progressively tighter abatement scenarios. The results in Figure 6-15 demonstrate that ECLIPSE is able to represent potential impacts of abatement policies on economic activity, with the economic cost of achieving the less-stringent targets being almost insignificant, but the marginal impact increasing with progressively more stringent abatement targets. It should be mentioned that the curves illustrating the impact on GDP are not entirely smooth, but the slight fluctuation is insignificant and an artifact of the iterative solving algorithm used in ECLIPSE being stopped before perfect convergence was achieved.

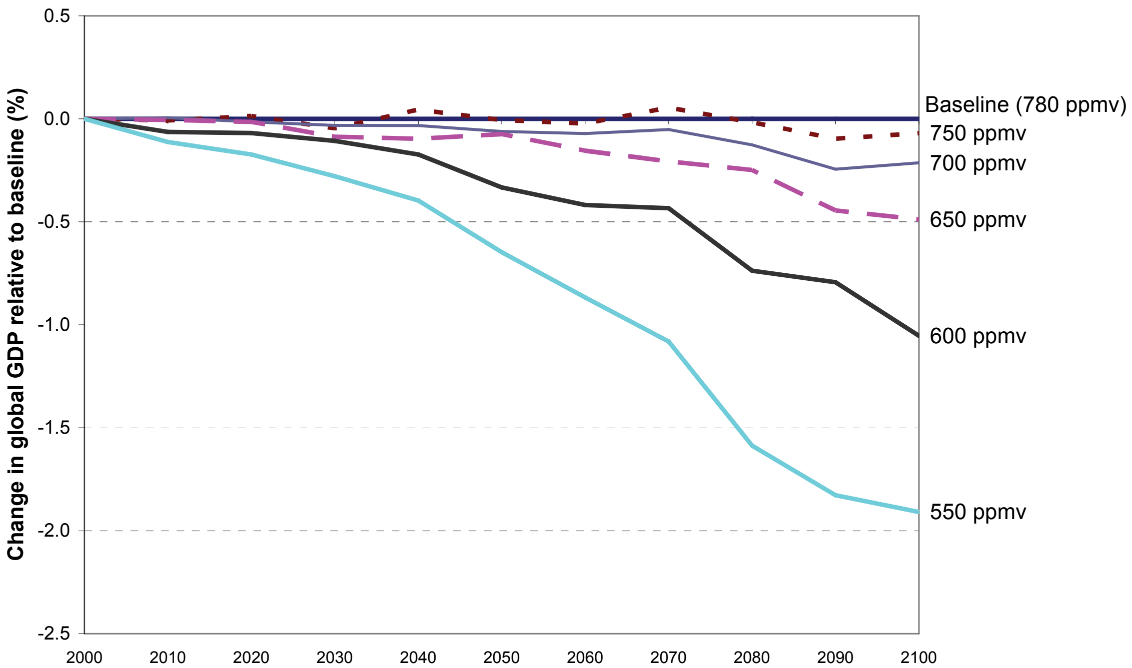

Figure 6-15 Impact on global GDP of a series of atmospheric CO_2 concentration targets

As mentioned above, we now look in more detail at the baseline case and the 550 ppmv mitigation policy scenario (hereafter referred to as the 550 ppmv case), to explore some of the features that make ECLIPSE suitable for examining climate change and other policies.

6.3.5 Results for the baseline and 550 ppmv scenarios

The combination of models incorporated in ECLIPSE makes it suitable for exploring a range of possible impacts arising from policy measures or market changes. This subsection seeks to further demonstrate some of the features of ECLIPSE by examining in more detail some of the policy-relevant results derived from the 550 ppmv mitigation case presented in Figure 6-15.

We turn first to estimates of global GHG emissions under a range of different assumptions and modelling approaches, presented in Figure 6-16. Figure 6-16 shows the results for global net emissions from all sources and sinks under the baseline (both ERIS-only and ECLIPSE) and 550 ppmv policy cases, as well as the difference in economic output between the ECLIPSE baseline and 550 ppmv cases. The divergence in emissions between the two baselines (ERIS and ECLIPSE) occurs because, as discussed in Section 6.3.3, energy demands in the ECLIPSE baseline are generally below those in ERIS as a consequence of the price response.

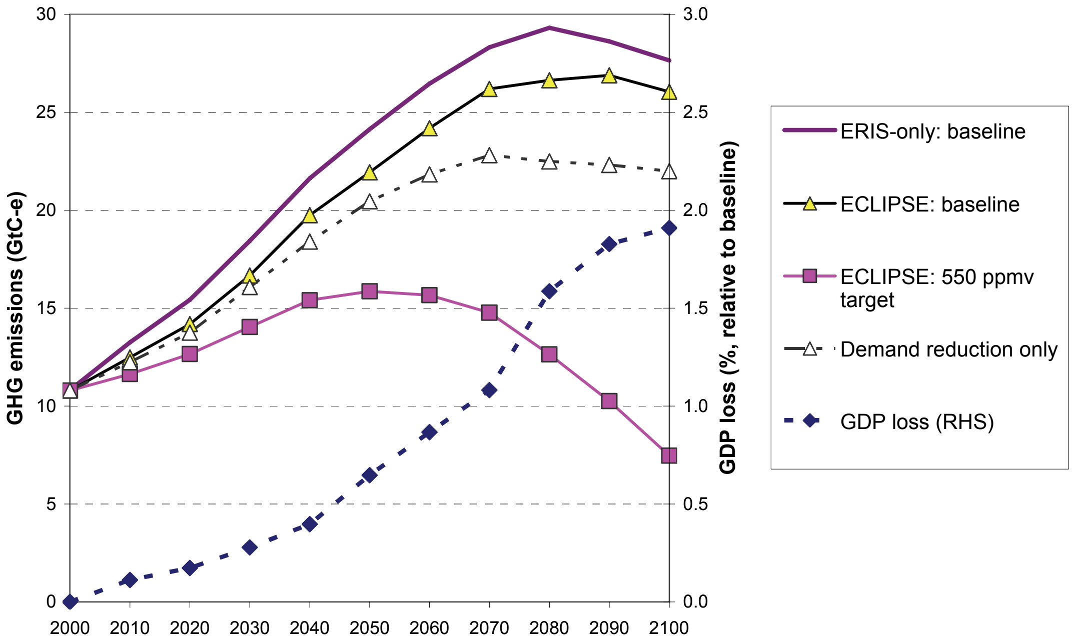

Figure 6-16 Global GHG emissions (all gases) under baseline and 550 ppmv scenarios, and GDP losses under 550 ppmv scenario

Looking now at the impact of the abatement policy, GHG emissions under the ECLIPSE baseline and 550 ppmv cases begin to diverge early in the century, and by 2100 global emissions under the mitigation scenario are reduced by around two-thirds compared to the baseline, whilst global GDP is around 2 percent lower. This loss of economic output is comparable to the results reported by Messner and Schrattenholzer (2000), although their findings were based on a less carbon-intensive baseline. Cumulative CO_2-equivalent emissions over the century are roughly 38 percent lower in the 550 ppmv case compared to the ECLIPSE baseline. In addition, the peak in global emissions is brought forward by roughly 40 years by the mitigation policy. Economic losses peak in 2100, which occurs as a result of the combined impact of a desire to minimise discounted energy costs (in ERIS) and discounted utility losses (in the macroeconomic model), and the ‘when’ flexibility of abatement.

However, one important additional feature of ECLIPSE, compared to bottom-up models, is its more extensive ‘how’ flexibility of mitigation. To illustrate this feature, Figure 6-16 also presents a “demand reduction only” GHG emissions trajectory, generated with the ERIS model using the energy and transport demands estimated in the ECLIPSE 550 ppmv case (but otherwise leaving GHG emissions unconstrained).[75] This helps to show how much of the GHG abatement in the 550 ppmv case is attributable to energy demand reductions, as opposed to ‘bottom-up’ energy and transport technology changes, non-CO_2 abatement and sequestration—noting that energy and transport demands are identical in the “demand reduction only” and “550 ppmv” emissions trajectories. Figure 6-16 shows that under the assumptions used here energy demand reduction makes a significant contribution to cumulative abatement over the century, accounting for more than one-quarter. However, the contribution in 2100 (22 percent) is slightly smaller than earlier in the century—for example, the share of abatement accounted for by demand reductions is roughly 30 percent in 2010, 2020, 2040, 2070 and 2080. The larger relative importance of demand reductions earlier in the century highlights how ECLIPSE is able to use ‘how’ flexibility to avoid costly fuel-switching options in preference for demand reduction. From a policy-making perspective, this illustrates the potential importance of measures to promote energy efficiency, particularly where supply-side abatement options are expensive, through instruments such as appliance and equipment performance standards, incentive programs, and removal of market distortions that discourage efficiency. However, it is important to note that the lower energy demand results in less scope for learning-by-doing, and this may favour incumbent technologies, many of which are fossil-based (as discussed in Section 6.3.3). This highlights a possible need for policy co-ordination, where abatement policies focused on demand reduction may eliminate some of the energy market conditions that are conducive to the uptake of new technologies. Without complementary technology support policies, such as R&D funding, feed-in laws, rebates and procurement programs, this may make further abatement more costly.

To illustrate additional features of the ECLIPSE 550 ppmv case, it is useful to briefly look at the energy and transport demands in more detail to explore the extent to which the macroeconomic and transport models in ECLIPSE substitute between energy and other inputs. Figure 6-17 and Figure 6-18 present energy and transport demands under each scenario and show that almost all demands are reduced under the 550 ppmv mitigation policy, with the notable exception of automobile travel. Higher automobile travel under the abatement policy may initially seem counterintuitive, but needs to be viewed in conjunction with demand for air transport, which is around 35 percent lower in the 550 ppmv case in 2100, as shown in Figure 6-18. This means that car transport is partly substituting for air transport under the GHG cap, mainly because increased energy costs associated with GHG abatement reduce the purchasing power of the travel money budget, promoting a shift to the cheaper transport mode.[76] Nonetheless, although transport consumption varies with price, it needs to be considered that the transport model in ECLIPSE assumes that the transport money budget share of income is constant and independent of transport prices—meaning that we do not allow direct substitution of passenger transport with other goods and services.

Combined with this relatively inelastic demand for car transport, the results in Figure 6-18 seem reasonable, and illustrate an important new feature of the ECLIPSE model compared to the other models discussed in earlier sections, which treat passenger transport in aggregate with other non-electric energy demands. Moreover, this result has some important implications for policy-makers. Specifically, it shows that the ancillary benefits of GHG

[75] That is, compared to the ECLIPSE baseline, this “demand reduction only case” includes the impact of the 550 ppmv abatement target on substitution of energy with capital and labour inputs (and substitution between different energy inputs), but does not include the impact on energy technology choices in ERIS, other than those resulting from lower demand—e.g., see Section 6.3.3.

[76] This is mainly because of the limited technology and fuel switching options in air transport. Other modes, particularly rail, including high-speed trains, would also be expected to substitute for air transport in this scenario.

abatement may not necessarily include a reduction in road congestion, urban air pollution or possibly even oil dependence. Accordingly, additional policies, such as road-user charges, emissions standards, and incentives for alternative fuels, may be required in conjunction with GHG abatement measures to achieve these other policy goals.

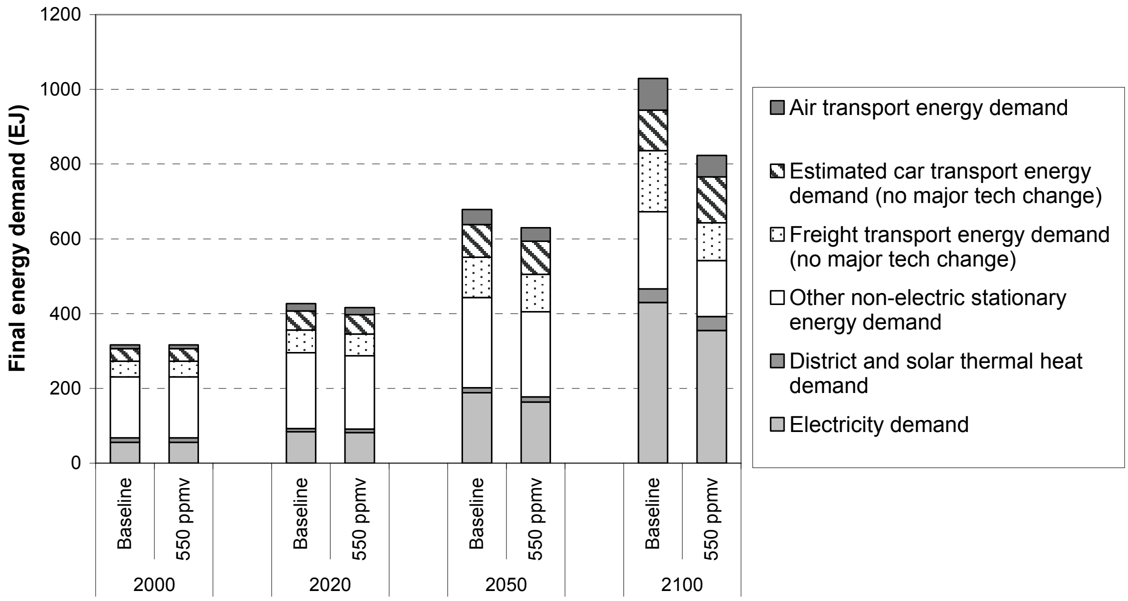

Figure 6-17 Global energy demand, baseline and 550 ppmv scenarios

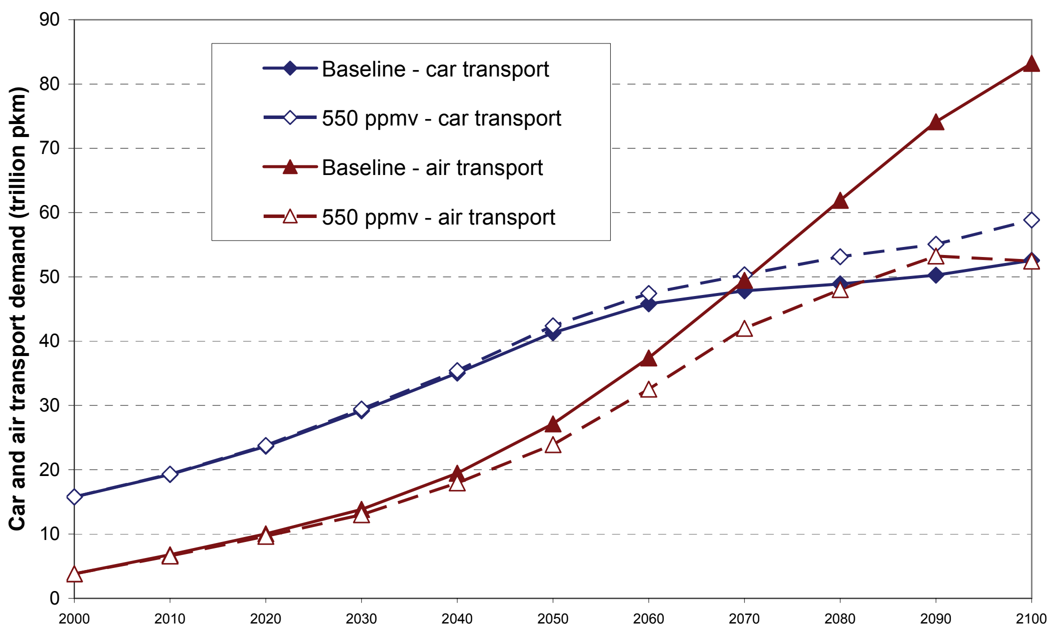

Figure 6-18 Global transport demands, baseline and 550 ppmv scenarios

Returning to the other demands presented in Figure 6-17, the mitigation policy reduces total electric, stationary non-electric and freight transport demand by similar absolute amounts by the end of the century. Electric and other non-electric stationary demands drop by around 17 and 27 percent, respectively—much more than the approximately 2 percent drop in economic output, highlighting the importance of substitution between different factors of production. However, the largest drop in energy demand is for freight transport (38 percent).[77] This is in marked contrast to automobile transport where relatively inflexible demand, arising from limited substitution possibilities is assumed. Moreover, freight demand is more responsive to price changes because of higher utilisation of freight vehicles compared to passenger vehicles, with energy accounting for a larger proportion of total costs, particularly for road freight. Consumers of freight transport respond to changes in costs through a combination of modal shift, and substitution of energy, capital and labour for transport, as described in Section 6.2.2.2. This implies that under the assumptions used here, freight transport may represent a promising target for GHG abatement because of opportunities to substitute other production inputs.

Finally, we turn to the comparative impact on atmospheric concentrations of CO_2, which is presented in Figure 6-19. These results were obtained with the MAGICC climate model (Hulme *et al.* 2000; Wigley and Raper 1997; Wigley 2003). Figure 6-19 shows that under the baseline scenario atmospheric CO_2 concentrations reach around 780 ppmv by 2100 and are still rising. In contrast, the GHG abatement policy restricts atmospheric CO_2 concentrations to 550 ppmv (by definition), with concentrations peaking in around 2090 under this case. Accordingly, the 550 ppmv policy represents a substantial departure from the business-as-usual scenario represented under the baseline. That the peak in CO_2 concentration occurs before 2100 under the abatement policy appears to indicate that the model is deferring some abatement to later in the century, when the additional technological learning opportunities can be realised, and also when abatement costs represent a smaller proportion of total economic output. This has a number of important implications regarding the 'when' of abatement action, although it is important to note that substantial abatement still occurs earlier in the century under this scenario (and the abatement policy significantly slows the rate of increase in atmospheric CO_2 concentrations during this period). This early action is also important as part of a hedging strategy when there is significant uncertainty about the ultimate level of abatement that is required.

This concludes the discussion of this illustrative baseline and abatement scenarios. The focus of this chapter is to outline the development, features and operation of an integrated policy assessment tool, rather than to analyse in more detail the specific abatement policy option used as an example above. However, the brief analysis presented above has helped to show how the modelling framework described in this chapter can elucidate some important policy insights. The following chapter (Chapter 7) presents in more detail results from the application of the integrated policy analysis tool to the emergence of a sustainable transport system over the 21st century, bringing together the main themes of this dissertation.

The results for both passenger and freight transport, in conjunction with the other results presented in this subsection, help to illustrate more broadly the type of analyses for which ECLIPSE is suited. For instance, although based on only two ECLIPSE model solutions,

[77] It should be noted that the freight transport energy demands in Figure 6-17 are presented in a way that excludes part of the impact of technological change in this sector. Specifically, there is a shift to fuel cell vehicles in this sector under the 550 ppmv scenario, which results in even lower energy demand.

these results indicate that ECLIPSE can generate a range of interesting policy insights for greenhouse gas abatement, including in relation to the transport sector. The detailed analysis in the following chapter uses ECLIPSE to explore further transport policy insights.

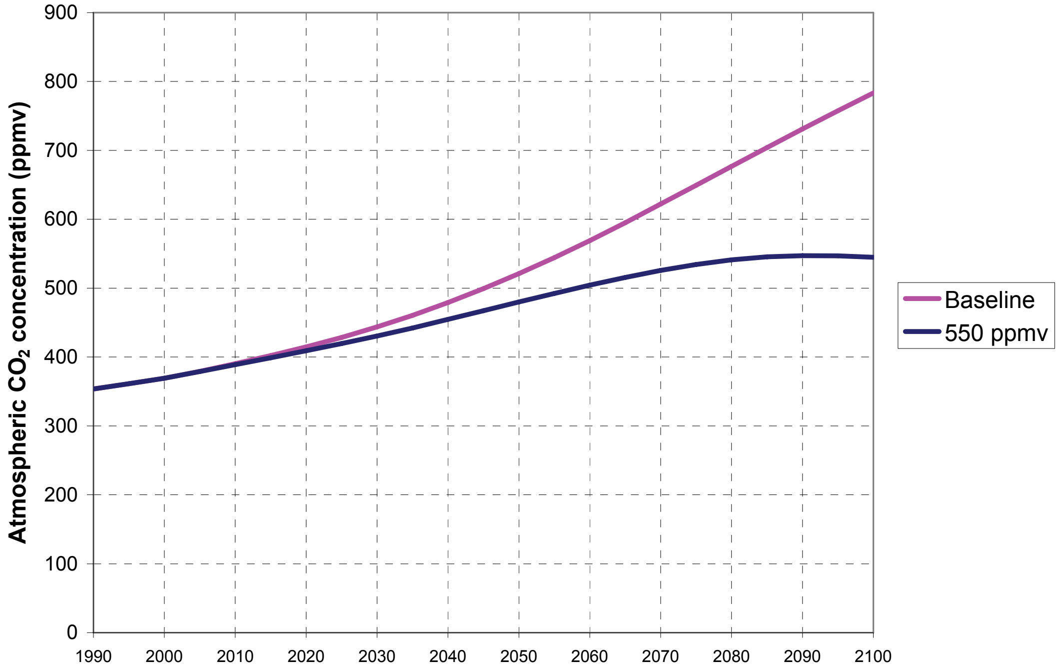

Figure 6-19 Atmospheric CO_2 concentrations, baseline and 550 ppmv scenarios

6.4 Conclusions

This chapter has described the development of a macroeconomic energy demand model and a consumer-budget transport demand model, and the linking of these to the bottom-up energy and transport system model ERIS. The proposed name for this integrated modelling tool is ECLIPSE (Energy and Climate Policy and Scenario Evaluation). ECLIPSE incorporates the advantages of a technology-rich energy system model with those of a macroeconomic model, whilst the separate modelling of passenger transport demand provides a realistic treatment of the factors driving demand in this sector.

This modelling framework captures several indicators of economic activity and welfare, including: energy system costs, regional consumer utility, regional GDP, personal mobility and environmental impact. These represent some of the multiple and competing objectives that policy-makers often seek to influence. Accordingly, the integrated framework presented here may be a useful tool for eliciting the trade-offs and synergies between these competing demands. Some results are presented that illustrate important differences between bottom-up and top-down modelling approaches, and indicate that bottom-up approaches may overestimate deployment and learning opportunities for new technologies. In addition, some features of the modelling framework are demonstrated with a simple exploration of abatement policy impacts.

This modelling framework also builds on earlier efforts to link top-down and bottom-up models. Some of the additional features combined here include: using a detailed production function formulation with four energy-transport inputs; calibration to ensure reproducibility of scenario parameters; including a consistent utility discounting framework; incorporating a separate passenger transport demand model; and dealing explicitly with model over-response. Nonetheless, many of the parameters used in this model are uncertain, and future work will seek to explore the sensitivity of some of the initial insights presented in this chapter to alternative parameter estimates.

We now turn in the following chapter to the application of this model to explore features of possible future development pathways for the global transport and energy system, with a focus on private passenger vehicle transport, that achieve the goals of sustainable development in terms of climate change mitigation, maintenance of security of energy supply, with a continuation of economic growth (see Box 2-1 in Chapter 2). In bringing together the main elements presented in Chapters 2 to 6, the following chapter synthesises many of the main findings of this dissertation with respect to realising a sustainable transport system.

Chapter 7. Sustainable global automobile transport in the 21st century: an integrated scenario analysis

7.1 Introduction

Realising the goals of sustainable development represents a significant challenge to humankind. The challenge of sustainable development—creating a livable future world in which human needs are met whilst maintaining the natural systems that support these needs—encompasses social, economic and environmental dimensions, and requires a long-term systematic perspective and the integration of many different elements. Critical among these elements are global energy and transport systems, and redirecting the development of these systems onto a sustainable path is becoming an increasingly important concern and policy objective (Schrattenholzer *et al.* 2004; IEA 2001a; Riahi *et al.* 2001; Barreto *et al.* 2003).

The current development trajectory of the global transport system, which is one important part of the overall energy system, poses a number of threats to sustainable development. These threats include the possible impact of anthropogenic climate change and risks to long-term security of the global energy supply. Looking first at climate change, there is mounting evidence of human interference with the Earth's climate system and this has led to concern about possible serious adverse impacts resulting from future global climate change (IPCC 2001a). Realising a sustainable transport system with a low impact on the global climate, but that still achieves other long-term development goals may require profound and wide-reaching changes (WBCSD 2004). Security of energy supply, on the other hand, is seen as a more pressing concern given the current overall dependence of OECD countries on oil supplied from politically volatile regions (e.g. IEA 2001b; EC 2001; DOC 1999). The combined impact of increasing global energy demand and eventual depletion of resources poses further serious long-term challenges to maintaining access to affordable and secure sources of energy, and appropriate policy responses may necessitate major changes to the global energy system.

Transforming global social and economic systems, including global transport systems, from their current structure to one that is compatible with sustainable development is likely to be a long-term process involving continual change to a range of physical, technological and institutional systems. Understanding how this long-term process might unfold may help guide policy responses aimed at achieving the long-term strategic goals of sustainable development. The objective of the analysis presented in this chapter is to explore one possible trajectory for the transformation of the global energy and transport system by building a long-term (until 2100) energy-economy-environment (E3) scenario. Such scenarios are useful for enhancing our understanding of highly complex systems, such as the future development of the global transport system, and for guiding responses to long-term challenges. Importantly, however, scenarios are not intended to be predictions, but enable us to explore plausible questions of "what if" related to key future uncertainties.

In this chapter we use an E3 scenario based on the B2 storyline from the IPCC's Special Report on Emissions Scenarios (Nakićenović and Swart 2000; Riahi and Roehrl 2000) to explore a number of issues related to the role of private transport and personal mobility in sustainable development. One of the specific questions we will attempt to address with this E3 scenario is if and how satisfying demand for personal mobility in the developed regions of the world, and achieving the mobility aspirations of the developing world, can be compatible with long-term sustainable development—defined here as encompassing economic growth, climate change mitigation and maintenance of security of energy supply. This will at very least provide an indication of whether it may be necessary to restrict access to particular modes of transport, even though this may undermine other aspects of development and human welfare.

Importantly, in this analysis we explore in detail only one possible configuration of the future global E3 system, even though significant social, economic, environmental, technological and political uncertainties mean that many pathways are possible. However, a single scenario that is carefully defined, internally consistent and intuitively plausible can provide important additional insights about technological developments and possible targets for policy support.

Moreover, this approach focuses the analysis on to the role of future technology choices in a possible transformation to a sustainable world. In this analysis we investigate in detail the transport sector technologies and energy carriers most characteristic of sustainable development (see Ausubel *et al.* 1998; Nakićenović 1991). The early identification of technologies with the potential to accelerate, or help overcome potential barriers to, the transition to a sustainable energy system is essential for providing guidance to policy makers about the most appropriate forms of support needed to achieve long-term sustainability strategies (Klaassen *et al.* 2002).

Within this context there has been a substantial debate on the role and possible early introduction of hydrogen (H_2) fuel and fuel cell (FC) vehicles in a long-term sustainable transport system (see e.g. Keith and Farrell 2003, Azar *et al.* 2003 and Wokaun *et al.* 2004). However, given that H_2 and FCs are immature and expensive technologies and much of the necessary supporting infrastructure does not yet exist, it is unclear along which pathways a so-called 'hydrogen economy' could emerge. This is one of the many issues this analysis will seek to explore. Moreover, transport systems based on alternative fuels such as hydrogen may not necessarily be compatible with sustainable development, since they may rely on energy-intensive synthesis pathways using fossil fuels. This highlights the importance of considering the transport sector in conjunction with the broader energy system, particularly fuel production.

Accordingly, for this long-term analysis we use ECLIPSE (Energy and Climate Policy and Scenario Evaluation), the integrated policy assessment tool described in Chapter 6 (Turton 2005a), to estimate key scenario variables and ensure engineering consistency within the energy and transport sector, and to incorporate economic feedbacks on energy and transport demand. ECLIPSE also includes endogenous technology change, and a detailed representation of transportation technologies. In this chapter we apply ECLIPSE to develop a technological road map to a sustainable transportation sector.

Given this overall plan, the remainder of this chapter is organised as follows. In Section 7.2 we describe some of the main elements of the scenario used in this analysis, including updates to the scenario presented in Chapter 3, and key assumptions about the implementation of sustainable development. Section 7.3 then very briefly describes the ECLIPSE modelling framework used in this analysis (which was presented in detail in Chapter 6). The results of the analysis are presented in Section 7.4 where we focus on the role of new technologies and fuels. Section 7.5 discusses some policy and technology development insights, related particularly to potential targets for public support to facilitate the realisation of a sustainable transport and energy system.

7.2 Scenario drivers for sustainable development

7.2.1 Basic scenario drivers

To explore the possible emergence of a sustainable transport system we apply the B2 scenario presented in Chapter 3, which encompasses suitable demographic, economic and social driving forces. As mentioned earlier, this scenario avoids heroic or utopian assumptions, does not diverge significantly from historical and prevailing trends, and relies on existing institutional frameworks. By using such a scenario we can assess whether these frameworks and trends are incompatible with sustainable development, and hence whether there is a need to break from existing structures. Nonetheless, future developments are highly uncertain, and no single scenario can encapsulate the inevitable and unpredictable political and other developments likely to occur over the timeframe of this analysis. However, by restricting the socio-political scope of this analysis to a scenario based on existing institutions and current trends in many world regions, the results presented in subsequent sections may have greater near-term relevance and can be directly understood in terms of current institutions and drivers.

For this analysis we updated the B2 scenario driving variables to account for actual changes between the base year used in the SRES (1990) and 2000, and to include revisions to future population projections (UN 2004). Specifically, we used the actual year 2000 population estimates and the latest UN medium population projections to 2100 instead of the 1998 UN medium projections employed in the SRES for long-term population growth under the B2 scenario. This ensures that the scenario used here is consistent with up-to-date median population growth trajectories. Figure 7-1 shows the population in each world region over the period 2000-2100 under this scenario, and compares the total population with the SRES B2 population scenario (labelled UN 1998 medium projection).

In addition, we applied B2 economic growth rates from the year 2000 onwards, and used actual estimates of GDP in 2000 rather than the SRES-projected levels of GDP (for a comparison between the SRES and actual developments between 1990 and 2000, see van Vuuren and O'Neill 2005). Economic growth in each world region is presented in Figure 7-2. We also calibrated the scenario to year 2000 energy demands (IEA 2003a; IEA 2003b), and used B2 energy intensity projections to calibrate the modelling framework described briefly in Section 7.3 (and in more detail in Chapter 6).

7.2.2 Transport scenario

As alluded to throughout this dissertation, future transport demand is uncertain, but there is an expectation that transport activity will experience rapid growth over the 21st century as incomes in developing countries rise, with a concomitant increase in energy consumption.[78] In passenger transport, without either a substantial reduction in demand for mobility or a shift towards public transportation (mass transit), both of which run counter to current global trends, curtailing this growth in energy demand is a significant challenge.

[78] For example, some of the nearer-term projections suggest that global transport energy demand could increase to 120-135 EJ by 2020 (EIA 2002; IEA 2004), with the lower estimate consistent with consumption of 145 EJ by 2030 (IEA 2004), compared to around 80 EJ in 2000.

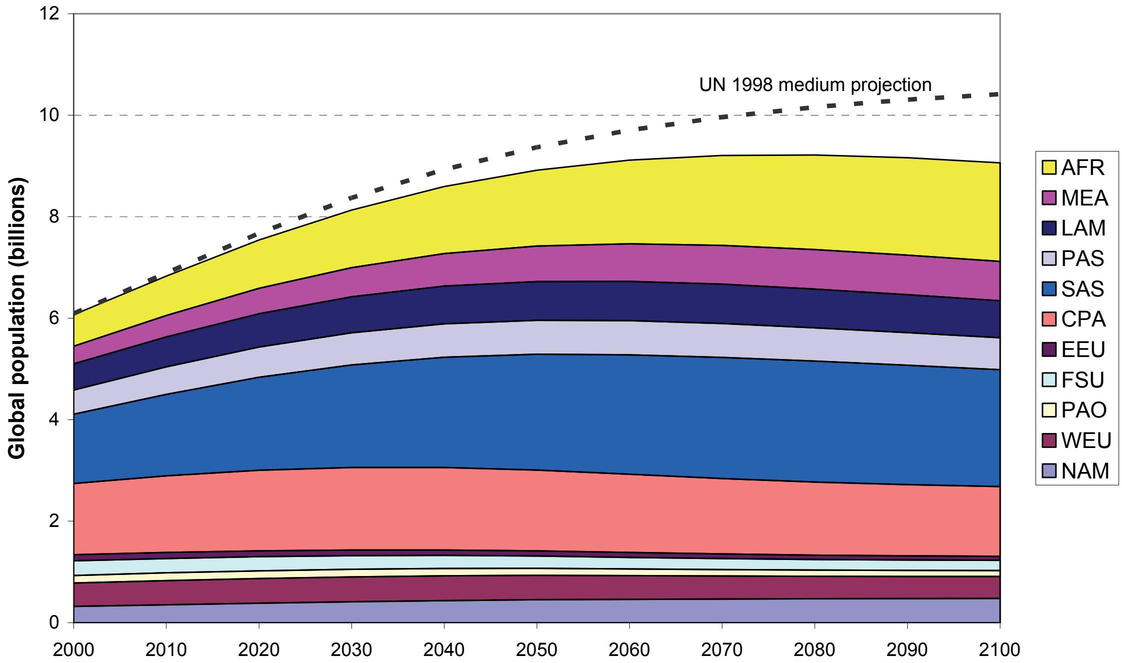

Figure 7-1 Global population scenario, UN 2004 medium projection

Source: UN 2004

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

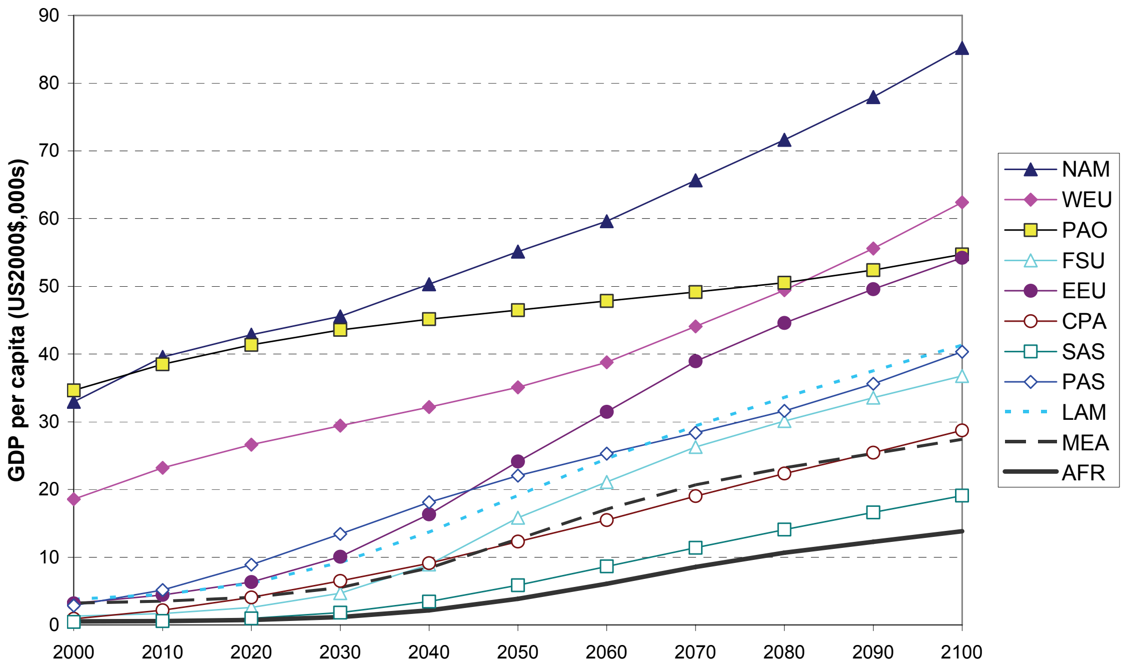

Figure 7-2 Economic growth scenario, based on SRES B2

Source: derived from Miketa 2004, Riahi and Roehrl (2000) and Riahi (2005)

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

In this subsection, we apply the broad socioeconomic drivers from the updated B2 scenario described above to develop an updated long-term scenario of automobile transport demand. Apart from the revisions to the socioeconomic drivers, the methodology applied here is identical to that presented in Section 3.2.2 in Chapter 3. Accordingly, the updated scenario of future passenger transport demand to 2100 reflects a continuation of many current trends. Using this approach, and the basic B2 scenario drivers described in Section 7.2.1 (and Section 3.2), we developed the automobile transport demand projection presented in Figure 7-3, in which total demand increases by around 250 percent over the century (an average of 1.26 percent pa). Similar to the scenario in Chapter 3 (Section 3.2.2.1), most of this growth occurs in developing regions, whereas in developed regions a combination of low population growth (or a decline), and a shift to faster modes of transport mean that total demand in 2100 is at around the same level as in 2000. Since these regions account for more than 80 percent of 2000 demand, the demand projection presented in Figure 7-3 implies an average 15-fold increase in developing country automobile travel demand. In conjunction, we developed an air transport scenario consistent with this automobile demand projection, in which global air transport demand increases by more than 21-fold between 2000 and 2100 (similar to the baseline demand growth scenario shown in Figure 6-18 in Chapter 6). To repeat, this multi-modal scenario differs to that presented in Section 3.2.2 of Chapter 3, but only because of an updated population projection is used here, as discussed above. That is, this 'what if' transport scenario still does not envisage a major shift to greater use of public transport (mass transit), a redesign of urban areas, or any significant attenuation of demand growth arising from information or communications technology, consistent with other aspects of the B2 storyline.

Having developed this scenario, we use it to calibrate the models used in this analysis, as discussed in Section 7.3.

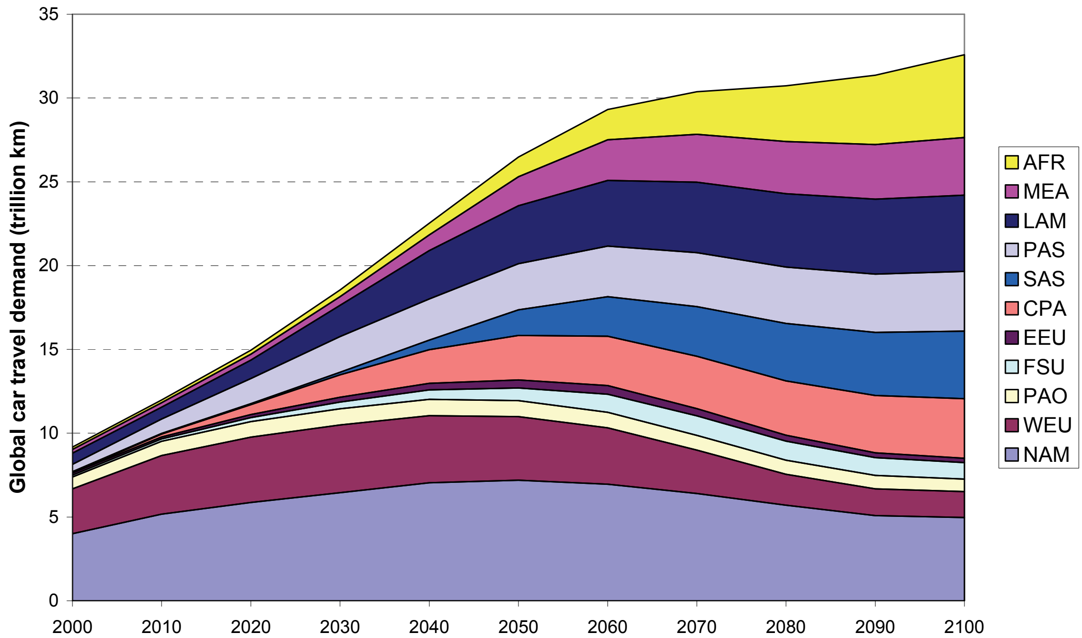

Figure 7-3 Automobile transport, calibration scenario

NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

7.2.3 Sustainable development objectives

Another key driver assumed in the sustainable transport scenario described in this chapter is sustainable development. As discussed in Section 7.1, we focus on three key aspects of sustainable development. The first of these is continuing economic growth, with a moderate reduction in income disparities between different world regions. This is represented by the economic growth trajectories presented in Figure 7-2. Although substantial differences in income persist under this growth scenario, there is a considerable improvement in distribution of income. For instance, it is possible to calculate a global Gini index (Gini 1921) from the information in Figure 7-1 and Figure 7-2, and this index improves substantially from around 71.5 in 2000 to 36.7 by 2100.[79]

The second element of this sustainable development scenario is related to the need to ensure access to energy supplies, which implies a need to manage effectively long-term threats to security of energy supply. This encompasses reducing exposure to the risk of supply disruptions by a combination of diversification, demand reduction, and maintaining domestic production capacity and resources. In developing this scenario, this is assumed to be implemented on a regional level and global level. Regionally, those regions most dependent on oil and gas from external sources are assumed to maintain an aggregate resources-to-consumption ratio of 20 years and maintain capacity to ramp up production rapidly in the first half of the 21st century, as described in more detail in Section 5.3.1 and Turton and Barreto (2006). It is also assumed that efforts are made to maintain the global resources-to-production ratios (Rsc:P) for oil and gas above 30 years throughout the century as a hedge against unforeseen requirements or supply disruptions.[80] Clearly, resource assumptions affect the stringency of measures aimed at achieving this goal. In this scenario, we again apply resource estimates from Rogner (1997) for oil and gas that include conventional reserves and resources, enhanced recovery, identified unconventional reserves and unconventional resource estimates (Categories I-VI using Rogner's notation)—for oil this is equivalent to roughly 5,500 billion barrels, which is consistent with other recent estimates (for example, see Odell 2004)—see Sections 3.2.3 and 5.2.1 for more details on resource estimates.

The third element of sustainable development included in this analysis is the need to mitigate climate change through greenhouse gas emissions abatement. In developing the scenario described in this chapter, we assumed that global efforts seek to limit atmospheric carbon dioxide (CO_2) concentrations to 550 ppmv or below throughout the 21st century, with concentrations declining at the end of the century. Although stabilising atmospheric concentrations to a lower level could be expected to further reduce the risk of climate change, 550 ppmv has been selected as sustainable development target that is achievable, without unexpected technology breakthroughs, given that current atmospheric concentrations are already approaching 380 ppmv (see Figure 2-3 in Chapter 2).

The following section briefly describes the methodology applied to combine these scenario drivers and thereby explore the possible emergence of a sustainable transport system.

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[79] Although not directly comparable to within-country Gini indices, for illustrative purposes the level of the global index in 2000 exceeds the level in some of the countries with the largest income disparities, such as Namibia, Colombia and Sierra Leone, while the index in 2100 is similar to countries with more moderate distributions such as Australia and the United Kingdom (UNDP 2004).

[80] It should be noted that this resources-to-production ratio differs from the commonly quoted 'reserves-to-production ratio', which is calculated based on identified reserves at a given point in time (which is a function of, among others, technology and prices), rather than ultimately recoverable resources.

7.3 Modelling framework: the ECLIPSE integrated policy analysis tool

The possible transition towards a sustainable passenger transport system cannot occur in isolation to developments in the overall energy system or broader economy. To ensure that such developments and interactions are considered, this analysis uses the ECLIPSE (Energy and Climate Policy and Scenario Evaluation) integrated assessment model—described in Chapter 6 (and in Turton 2005a). This model incorporates the detailed bottom-up energy systems model ERIS described in Chapter 3 with macroeconomic and passenger transport demand models. Accordingly, ECLIPSE models and integrates feedbacks between economic activity, transport demand and the energy system iteratively. In addition, the linkage described in Chapter 3 between the ERIS model and the MAGICC climate model (Wigley 2003; Wigley and Raper 1997) is retained. This combination of features makes this integrated model ideally suited to analysing the technological, economic, resource and environmental implications of future transport demand.

All of these models are described in detail elsewhere in this dissertation, and the only further modification worth noting is the inclusion of an additional hydrogen production technology into the ERIS modelling framework. Specifically, hydrogen production from electrolysis using baseload electricity is included (based on data from Simbeck and Chang 2002).

The application of this integrated modelling framework to the scenario developed using the key drivers described in Section 3.2.1 and Chapter 3 (and updated as described in Section 7.2) is presented below.

7.4 Scenario results

7.4.1 Sustainability indicators

The main driving forces under this scenario include continuing economic growth, climate change mitigation, and enhancement of long-term energy resource security (see Section 7.2). To illustrate the impact of these drivers, a number of key indicators of sustainable development are presented in Figure 7-4, including atmospheric concentrations of CO_2, the global resources-to-production ratios (Rsc:P) for oil and gas, and economic output. These macro indicators are calculated from the output of the modelling framework described in Section 7.3 (and Chapter 6), based on the scenario described in Section 7.2. Figure 7-4 shows that under the sustainable transport scenario developed in this analysis, global atmospheric CO_2 concentrations peak at 550 ppmv in around 2085, global Rsc:P ratios stay above 40 years throughout and are increasing at the end of the century—that is, they stay above the 30 year policy target described in Section 7.2.3—and economic growth continues throughout the century.

For comparison, in the absence of sustainable development drivers, global atmospheric CO_2 concentrations would reach over 800 ppmv by 2100,[81] and global Rsc:P ratios would fall well below 20 years using the same modelling assumptions (results not shown). On the other hand, under the assumptions applied here global economic output would be around 2 percent higher by the end of the century without the sustainable development drivers, although this estimate excludes the possible negative economic impacts of climate change or reduced supply

[81] This concentration differs from the figure presented for the baseline in Chapter 6 because of the recalibration discussed in Section 7.2.1.

security. This 2 percent difference in economic output can be compared with the 750 percent increase in global GDP over the century (equivalent to 88 percent of the 2100 level).

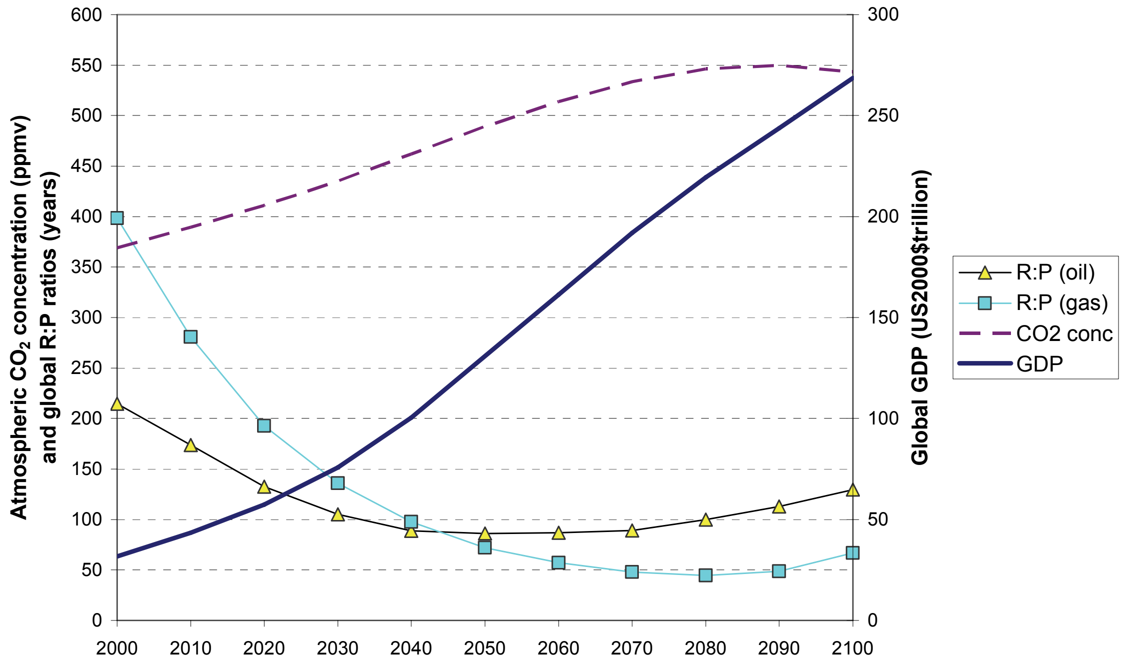


Figure 7-4 Sustainable development indicators

This implies that it is possible to achieve some aspects of long-term sustainability in the energy system for a relatively small economic cost over the course of the 21st century. We now turn to the focus of this chapter (and the second theme of this dissertation), which is to explore the implications of this scenario for the global transport system.

7.4.2 Global transport energy consumption

As outlined earlier, future passenger travel demand poses a potentially significant challenge to sustainable development. However, the results above show that it is possible to describe a long-term transition to a sustainable energy system, implying that it may be possible to overcome this challenge. We now look in more detail at the transport sector within this scenario, to identify key developments required for long-term sustainability.

Figure 7-5 presents energy use in the transport sector, under this scenario, and shows both the transition from petroleum products to a more diverse fuel mix and broad technological developments. Figure 7-5 shows that total global transport energy demand increases roughly 200 percent over the 21st century, although without improvements in efficiency across all modes of transport this would be much higher—in this scenario it is assumed that average car efficiency improves slowly at a rate of 2 percent per decade (to account for efficiency improvements being offset by a shift to larger vehicles with more on-board systems), air transport efficiency converges towards 0.9 MJ/pkm, and other modes follow the overall transport sector efficiency improvements implied in the original B2 scenario, in which total transport energy demand also grows by around 200 percent (see Section 3.2.2 and Riahi and Roehrl 2000). Further efficiency improvements arise as a result of the deployment of new transport technologies, and this is partly illustrated by the increasing role of fuel cells shown in Figure 7-5, which contribute to the stabilisation of energy consumption towards the end of the century.

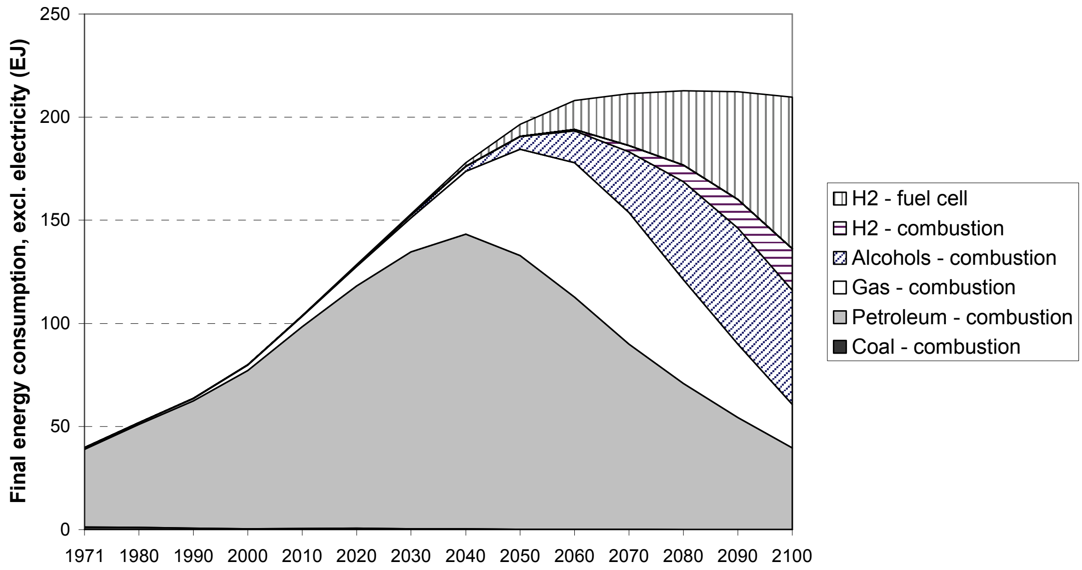


Figure 7-5 Transport energy consumption, historical and scenario

Source (historical statistics): IEA 2003a; IEA 2003b

The introduction of the fuel cell technologies begins around 2010, although initially in very limited quantities, but their share gradually increases such that they become an important technology by the end of the 21st century. Looking at energy carriers, first natural gas, then alcohols and hydrogen displace an increasing share of petroleum. Importantly, however, Figure 7-5 shows that there is scope within a sustainable development scenario for petroleum products to continue to play a substantial role in the transport system, and most of this petroleum is used in air transport towards the end of the century (along with direct combustion of hydrogen).

Air transport is a large consumer of energy in 2100 under this scenario, with energy demand increasing almost 450 percent over the century, as shown in Figure 7-6, which presents transport demand for three main sectors—automobiles, air transport and freight. In comparison, automobile transport demand increases 4-fold and freight transport energy demand 3-fold over the century. It should be noted that the transport demands presented in Figure 7-6 differ from the calibration demand discussed in Section 7.2.2, and presented in Figure 7-3 for automobile transport. These calibration demands are represented by dashed lines in Figure 7-6.

The differences between the calibration and actual scenario are most apparent for air and car transport, but also occur for freight transport, and arise because achieving the sustainable development objectives increases the cost of energy. Among other impacts, this leads to substitution of energy and freight inputs in economic production, resulting in a slight decrease in freight energy demand. For car and air transportation, the increased energy cost reduces the purchasing power of the travel money budget—resulting in a shift away from more expensive air travel to less-expensive car travel. It is important to stress that this impact arises not because of different relative increases in the cost of one mode compared to another, but instead as a consequence of the overall reduced purchasing power of the travel money budget, which tends to favour the cheaper transport mode. This is an important finding, because it shows that an even greater increase in car transport demand (than shown in Figure 7-3) can still be compatible with sustainable development, but it also implies that policies aimed at the two sustainable development drivers analysed in detail here—climate change mitigation and security of energy supply—may lead to negative impacts in terms of congestion and urban air pollution. However, new car technologies and fuels also have the potential to alleviate urban air pollution, along with reducing greenhouse gas emissions and reducing risks of energy supply disruptions. We now look at the choice of car technologies and fuels under this scenario in more detail.

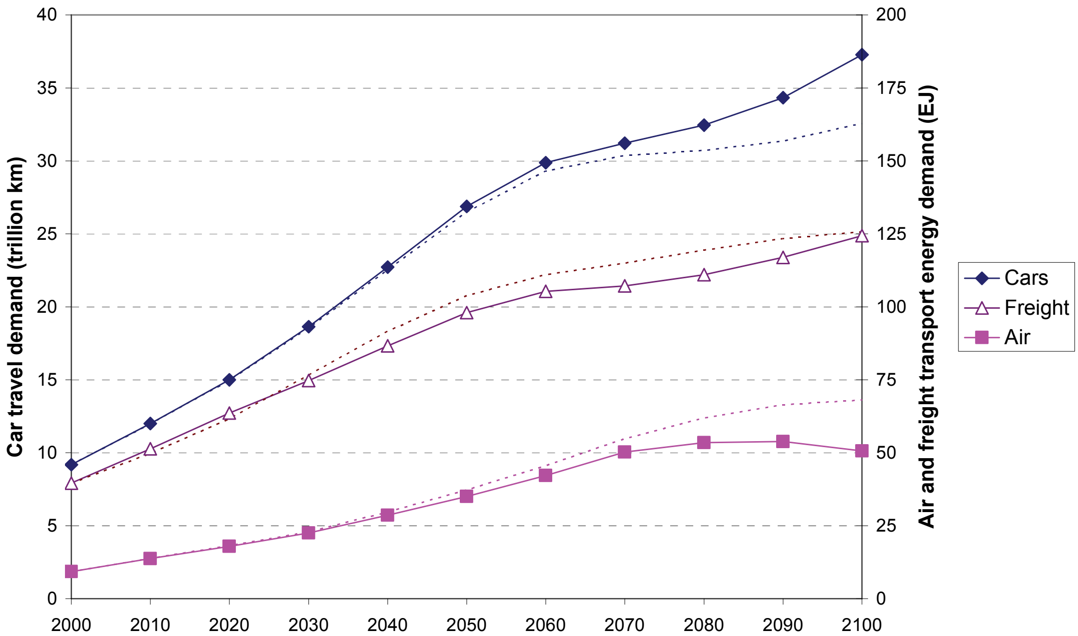


Figure 7-6 Transport demand, sustainable development scenario and comparison with calibration baseline

Note: the calibration scenario is indicated by the dotted lines.

7.4.3 Car transport

New technologies have the potential to play a major role in any transition towards a more sustainable transport system. The automobile technologies and fuel most compatible with sustainable development under the scenario described in this chapter are illustrated in Figure 7-7, which disaggregates total automobile transport demand into different technologies and fuels.

Figure 7-7 shows that in the first half of the 21st century hybrid ICE-electric technologies slowly begin to challenge the dominance of the petroleum ICE, and by 2030 account for almost 10 percent of travel. This increases to almost 55 percent in 2050, and peaks at 78 percent in 2070. Hybrid electric vehicles (HEVs) fueled with natural gas are initially the most attractive, with smaller shares of petroleum and alcohol HEVs also playing a role. The initial attraction of natural gas HEVs can be attributed to their low emissions and cost, and their reliance on a fuel that is more abundant than petroleum. However, towards the end of the century they are replaced by alcohol HEVs as the dominant hybrid technology, driven mainly be efforts to manage the depletion of gas resources, and to further reduce greenhouse gas emissions.

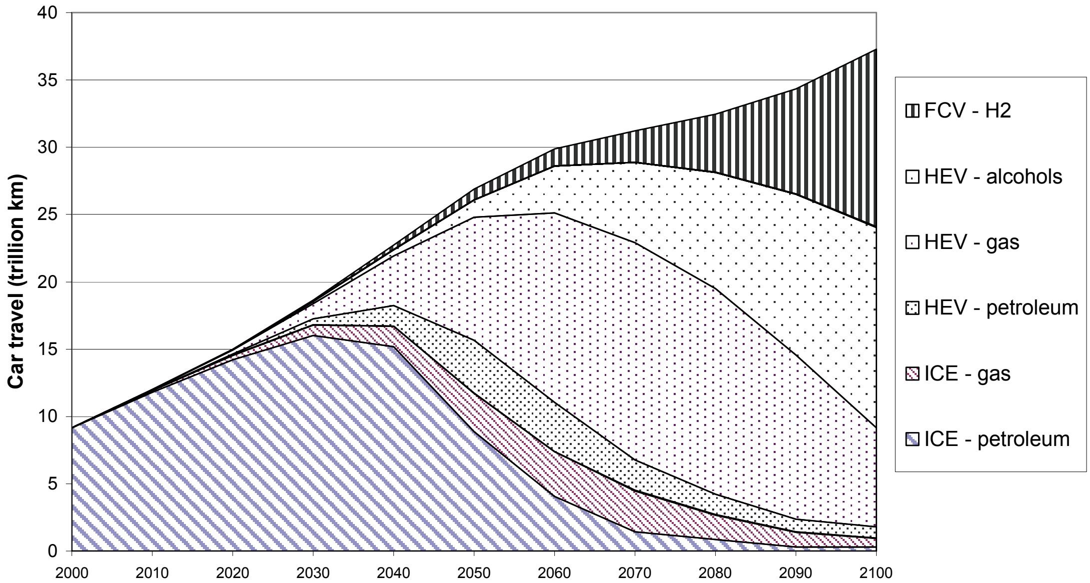


Figure 7-7 Technologies and fuels for automobile transport

Abbreviations are as follows: ICE—conventional internal combustion engine vehicle; HEV—hybrid ICE-electric vehicle; and FCV—hybrid fuel cell-electric vehicle.

Around the same time as alcohol HEVs start playing an increasingly important role in automobile transport, hydrogen-fueled fuel cell vehicles (FCVs) begin to be deployed in this sector on a larger scale. Under this scenario, the first transport applications in which hydrogen is deployed on a large scale are in heavy transport, where on-board storage and refueling do not represent as great a barrier as in private automobile transport (similar to the result observed in Section 4.2.1). The freight sector (including heavy transport) remains an important consumer of hydrogen throughout the century, and by 2100 accounts for almost half of global H_2 demand. By this time, more than one-third of the passenger fleet is also powered by hydrogen fuel cells. Fuel cells powered by other fuels—such as methanol or petroleum—do not play a significant role in this scenario, mainly because they face additional technical barriers associated with reforming the input fuel. Conversely, the role played by hydrogen fuel cells in automobile transport is limited for much of the century because of the availability of a number of alternative automobile technology–fuel combinations that can achieve high levels of sustainability, and also by limited availability of H_2 and the cost FCV drivetrains. It is important to note, however that in this dissertation we focus on a limited set of sustainability criteria, and efforts to address other sustainability issues—such as local air pollution—may increase the attractiveness of those transport technology options that are uncompetitive under this scenario.

7.4.4 Fuel production

The deployment of sustainable vehicle technology-fuel combinations described above depends critically on transitions in the global fuel production system, particularly the increasing availability of alcohol fuels and hydrogen. Initially, alcohol fuels have a number of advantages over hydrogen—they can be handled relatively easily and distributed utilising some of the existing fuel delivery infrastructure—and so play an important role in improving sustainability in this scenario before hydrogen supply infrastructure is fully developed, and fuel cells are mature. Importantly, throughout much of the century alcohols and hydrogen complement one-another, rather than compete, as they increasingly substitute for fossil fuels in surface transport. This is illustrated in Figure 7-8 which compares global petroleum production (refining) with production of alternative fuels over the century under this scenario. Again illustrating the continuing importance of oil, refinery throughput exceeds alternative fuel production for much of the century under this scenario, and it is not until 2080 that combined production of alcohols and hydrogen becomes larger the petroleum production.

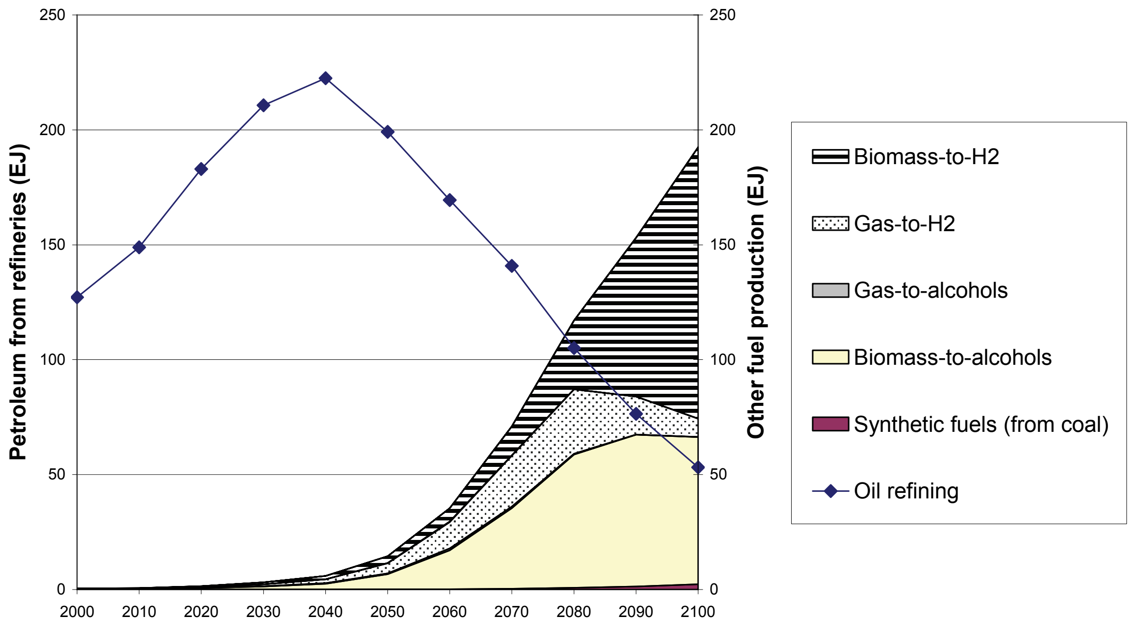


Figure 7-8 Global fuel production

The continuing reliance on petroleum fuels in this scenario occurs partly because of barriers to the mobilisation of technologies and sufficient resources for large-scale non-fossil synthetic fuel production and distribution, particularly from biomass. For instance, hydrogen is initially synthesised from natural gas, which is a more technologically mature production path relying on a conventional feedstock. Later, synthesis from biomass becomes the preferred production route for both hydrogen and alcohols. Under this scenario, hydrogen synthesis from biomass is also combined with carbon capture and storage (CCS) technologies, resulting in a fuel with net negative emissions.

Given the importance of biomass in this scenario it is worth briefly mentioning the biomass resource potentials assumed in the ERIS model. These potentials are based on estimates from Rogner (2000), who identified an annual global potential in 2050 of between 250 and 400 EJ, mostly in Africa and Latin America—which is similar to other estimates, such as in Fischer and Schrattenholzer (2000). In this scenario we assume that this potential can only be fully exploited towards the end of the century, and that in 2020 only 125 EJ is available, rising to 235 EJ in 2050 and 320 EJ by 2100. Nonetheless, realising even these potentials may be challenging, given competing demands for land and the need to achieve other aspects of sustainable development, such as maintaining biodiversity. We explore this in more detail in Section 7.4.7.

7.4.5 Well-to-wheels emissions

The penetration of zero- or negative-emissions alcohol and hydrogen fuels synthesised from biomass into the transport sector can be seen as an important element in the transition to a sustainable transport system. The overall impact of this transition on greenhouse gas emissions from automobile transport is illustrated in Figure 7-9, which shows partial well-to-wheels emissions,[82] and the specific emission factor of car travel under this scenario. Figure 7-9 also shows the impact of some of the other factors discussed above including improvements in efficiency, new technologies, fuel switching, and carbon capture and storage. Without any of these factors, emissions would have simply increased in line with car travel demand (which is shown in Figure 7-6) to over 2.8 Gt of carbon (C) in 2100. However, Figure 7-9 shows that the efficiency improvements unrelated to energy technologies assumed for this scenario—2 percent per decade (being the combined impact of factors such as reduced rolling resistance, better aerodynamics, lighter materials etc., partly offset by consumer preferences for larger vehicles)—reduce this by around 500 Mt C. Emissions are further reduced by the deployment of new efficient vehicle technologies such as hybrids and fuel cells, and by 2100 these technologies are responsible for almost 900 Mt C of annual abatement. As alluded to earlier, the single largest impact arises from a shift to low emissions fuels, which reduces emissions by over 1.1 Gt C in 2100, down to just above 300 Mt C. Carbon capture and storage in hydrogen production reduces this by around a further 100 Mt C, such that automobile CO_2 emissions in 2100 are less than one-third of their 2000 level.

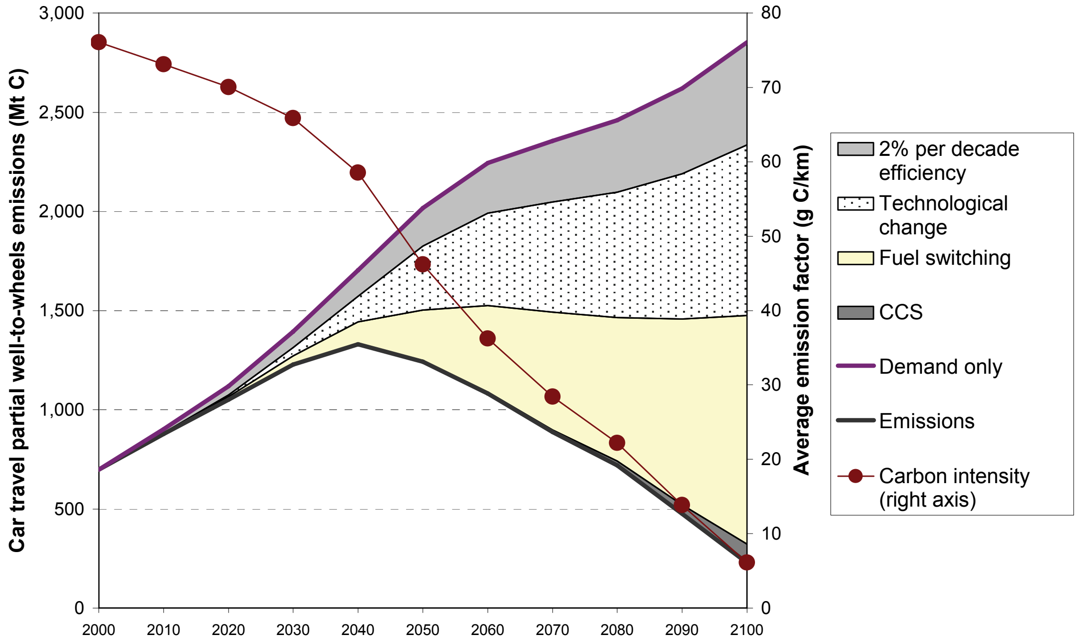


Figure 7-9 Partial well-to-wheels emissions for automobiles

[82] Partial well-to-wheels emissions presented in Figure 7-9 include emissions from fuel production and losses in transmission and distribution, but exclude non-CO_2 emissions (which arise, for instance from fertilisers used for biomass production, or from venting of gases during oil extraction), and emissions produced in the transport of fuels.

The combined effect of these factors reduces the average emissions per kilometre of travel by over 90 percent between 2000 and 2100. By many indicators automobiles become an increasingly sustainable transport option as the century unfolds in this scenario.

7.4.6 Other energy system developments

It is important to remember that the emergence of a sustainable transport system does not occur in isolation to other developments in the global energy market. This has already been discussed in terms of a shift to synthesis of alternative fuels, and is further illustrated by exploring developments in other energy sub-sectors. This helps to show how developments in the transport sector are part of a consistent and co-ordinated transition towards a more sustainable energy system. Figure 7-10 presents electricity generation and direct thermal consumption according to fuel in 2000, 2050 and 2100 under this sustainable development scenario. Apart from a strong shift towards greater use of electricity, because of its flexibility and convenience for the end user (which is an element of the B2 storyline (Nakićenović and Swart 2000)), Figure 7-10 illustrates a number of other important changes. In electricity generation, there is a transition away from coal initially towards natural gas and nuclear generation, and eventually nuclear and renewables. Although much of this nuclear generation is from inherently safe third and fourth generation reactors, this technology must overcome a number of other major barriers before it can be considered an option for sustainable development, related mainly to waste management and safety, public acceptance, and weapons proliferation. Looking at other fuels, only a small amount of hydrogen or biomass is used in electricity generation, because these fuels are required in other sectors. In comparison, the fuel mix used to satisfy direct thermal energy needs changes less over the century, with oil and gas remaining important, but surplus electricity and hydrogen being used in preference to coal and biomass. The overall global energy flows are presented for 2000, 2020, 2050 and 2100 in Figures 7-11 to 7-14, respectively.

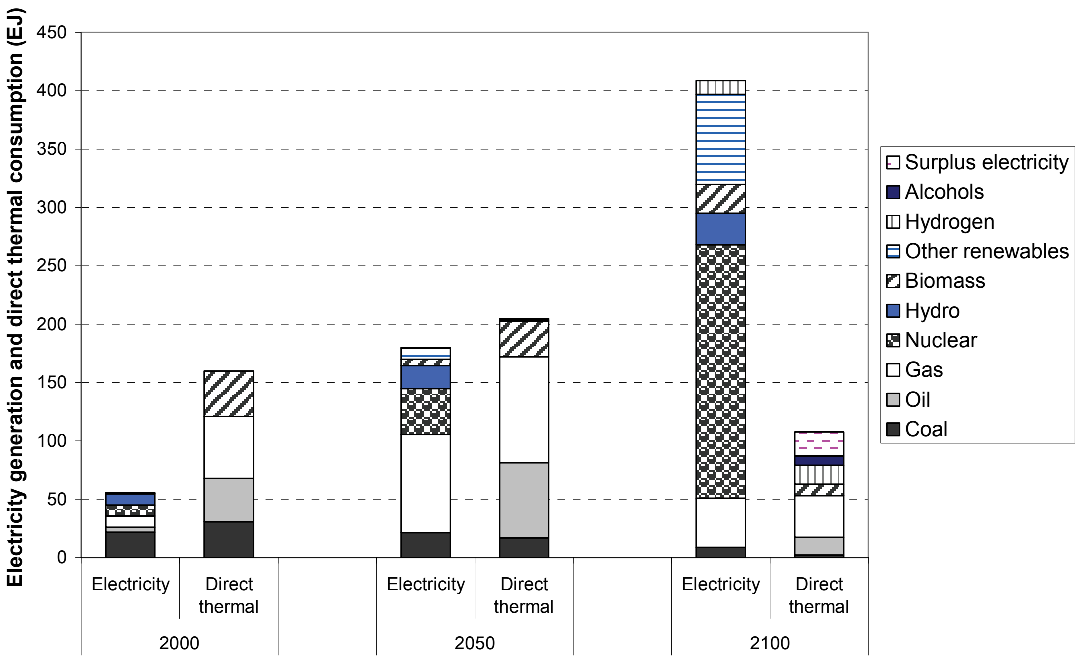
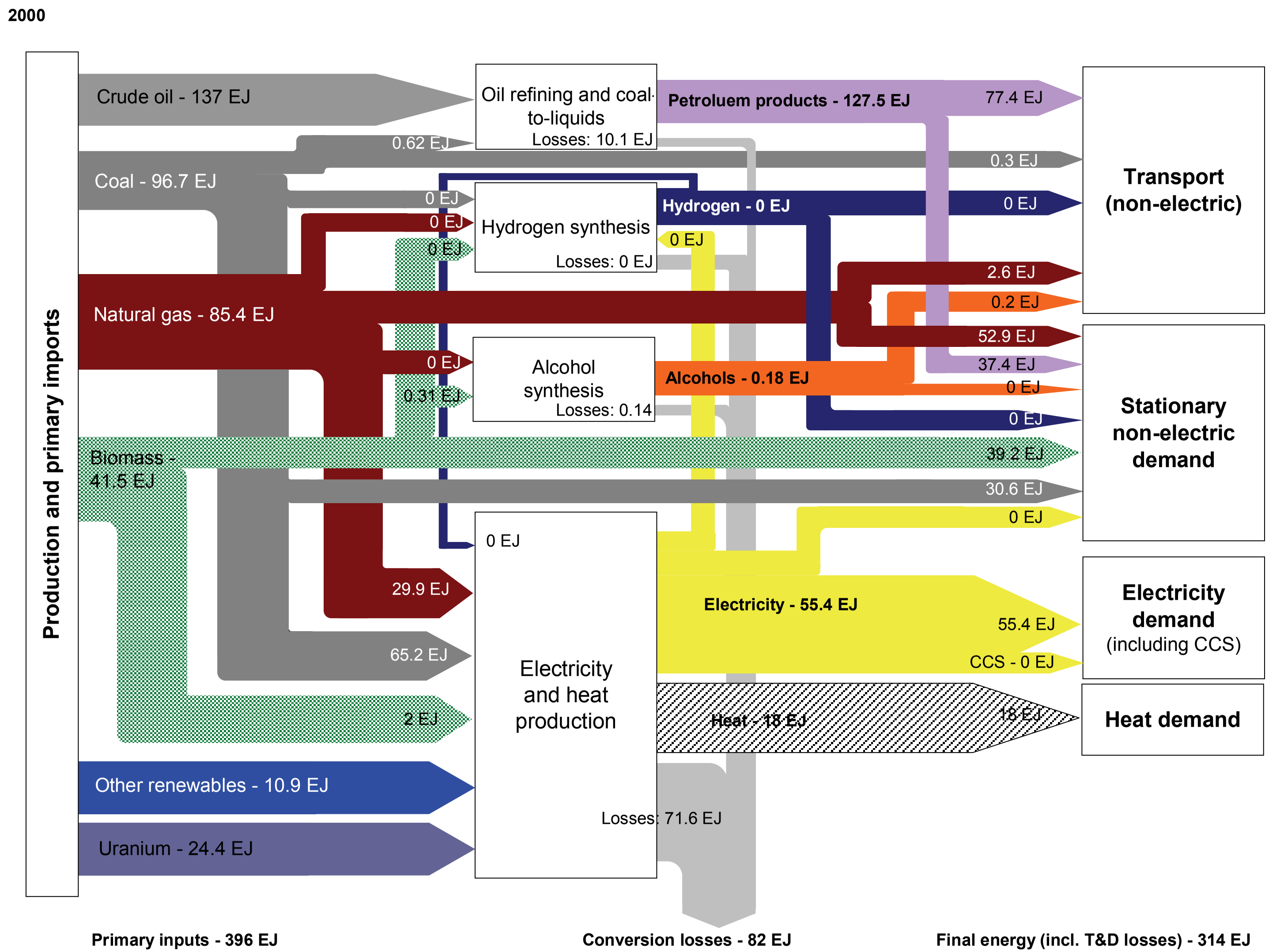


Figure 7-10 Global electricity generation and direct thermal combustion, by fuel



Transport breakdown

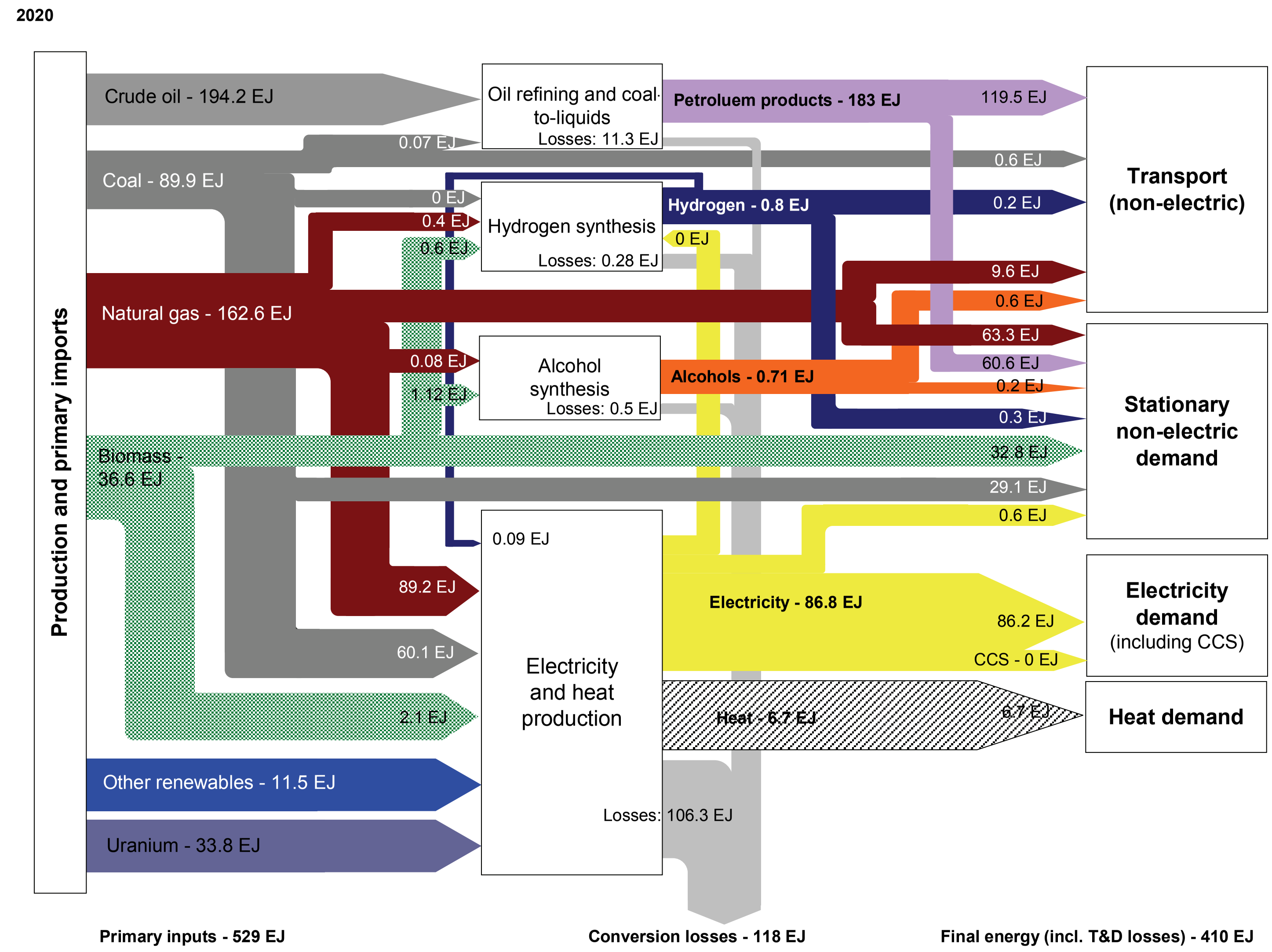
		Air	Car	Other
77.4	Petroleum	9.3	31.5	36.6
0.3	Coal	0.0	0.0	0.3
0	Hydrogen	0.0	0.0	0.0
2.6	Natural gas	0.0	0.0	2.6
0.2	Alcohols	0.0	0.0	0.2
80.5	Total	9.3	31.5	39.7

Carbon capture and storage

CCS from:	Mt C
* electricity production	0
* CTL production	0
* H2 production	0
Total	0

Figure 7-11 Global energy flow diagram, including transport subsectors and carbon capture, 2000

(note: flow widths are not to scale; heat demand refers to demand for district and solar thermal heating)



Transport breakdown

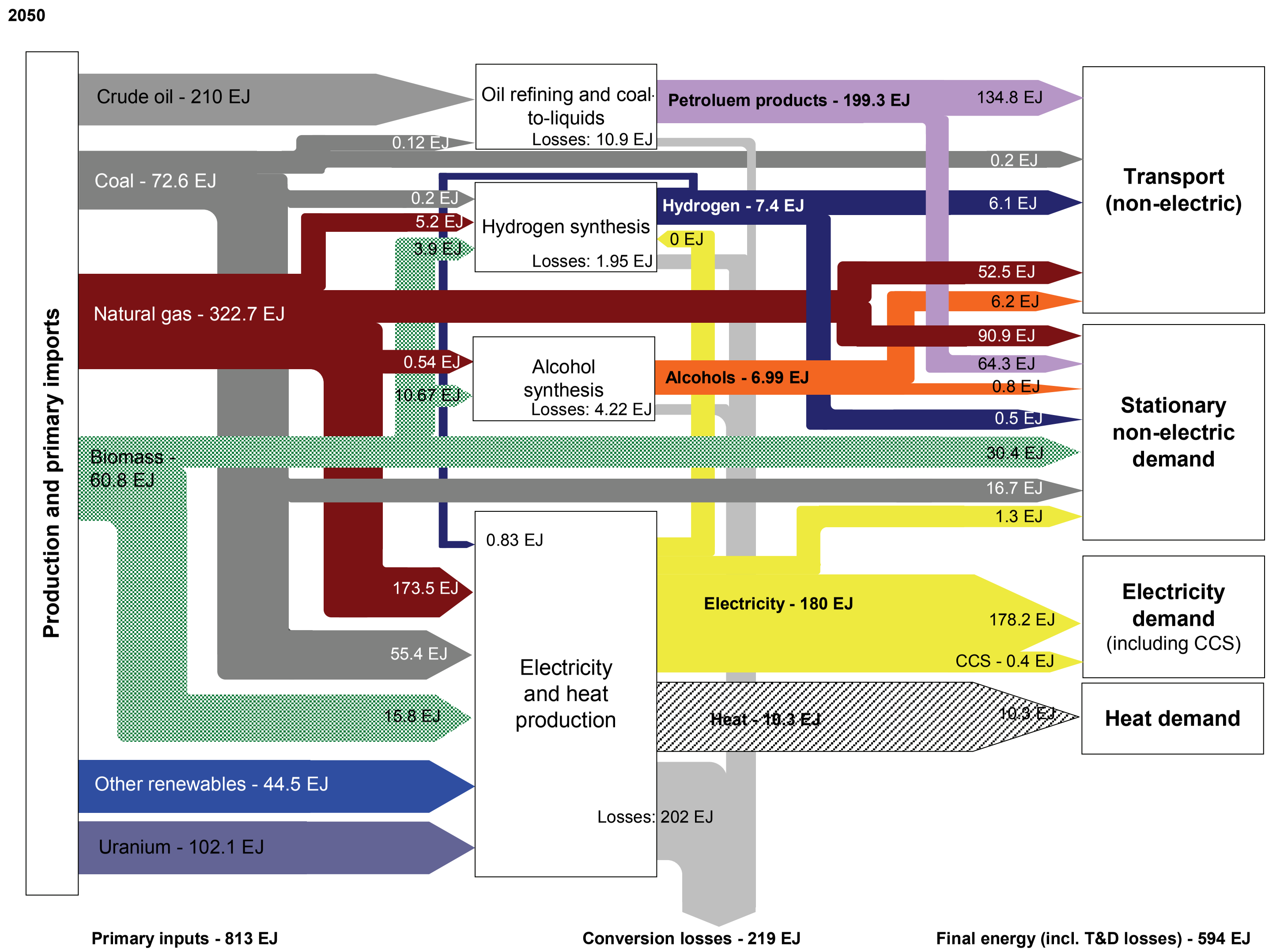
		Air	Car	Other
119.5	Petroleum	18.0	47.1	54.4
0.6	Coal	0.0	0.0	0.6
0.2	Hydrogen	0.0	0.1	0.1
9.6	Natural gas	0.0	1.7	7.9
0.6	Alcohols	0.0	0.1	0.4
130.5	Total	18.0	48.9	63.5

Carbon capture and storage

CCS from:	Mt C
* electricity production	10
* CTL production	0
* H2 production	4
Total	14

Figure 7-12 Global energy flow diagram, including transport subsectors and carbon capture, 2020

(note: flow widths are not to scale; heat demand refers to demand for district and solar thermal heating)



Transport breakdown

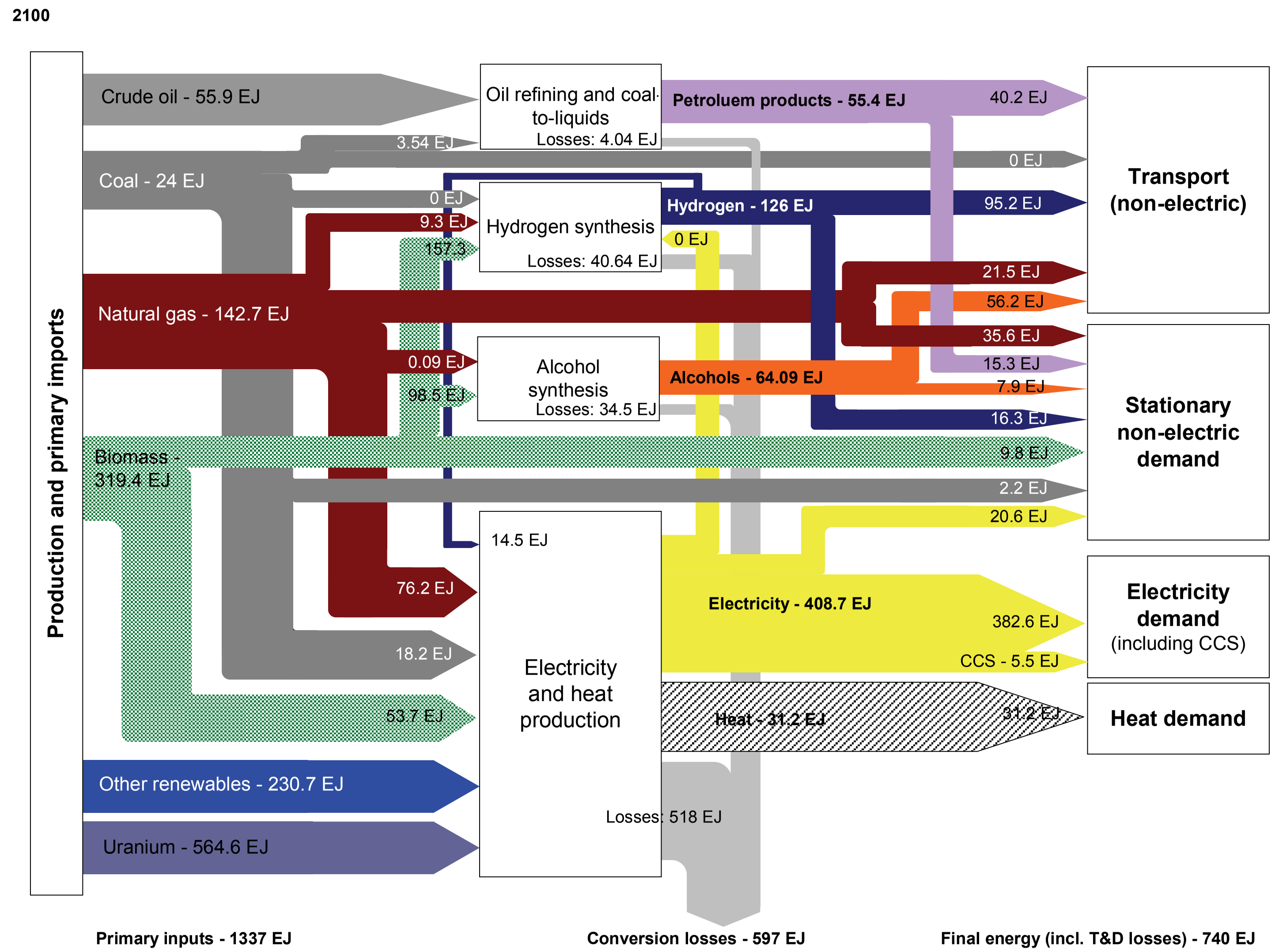
		Air	Car	Other
134.8	Petroleum	34.8	36.9	63.1
0.2	Coal	0.0	0.0	0.2
6.1	Hydrogen	0.2	1.3	4.6
52.5	Natural gas	0.0	28.0	24.6
6.2	Alcohols	0.0	3.0	3.1
199.8	Total	35.0	69.1	95.6

Carbon capture and storage

CCS from:	Mt C
* electricity production	91
* CTL production	2
* H2 production	29
Total	122

Figure 7-13 Global energy flow diagram, including transport subsectors and carbon capture, 2050

(note: flow widths are not to scale; heat demand refers to demand for district and solar thermal heating)



Transport breakdown

		Air	Car	Other
40.2	Petroleum	30.2	2.6	7.4
0	Coal	0.0	0.0	0.0
95.2	Hydrogen	20.4	17.5	57.3
21.5	Natural gas	0.0	16.1	5.4
56.2	Alcohols	0.0	30.7	25.5
213.1	Total	50.6	66.8	95.7

Carbon capture and storage

CCS from:	Mt C
* electricity production	1174
* CTL production	53
* H2 production	624
Total	1851

Figure 7-14 Global energy flow diagram, including transport subsectors and carbon capture, 2100

(note: flow widths are not to scale; heat demand refers to demand for district and solar thermal heating)

The developments and transitions in the non-transport energy sectors illustrated across Figures 7-11 to 7-14 are equally important for the emergence of a sustainable transport system, since they ensure that these other sectors do not overly compete with transportation for the fuels required to make the transition to sustainability. These main elements of an overall energy system compatible with sustainable development include:

- a fuel synthesis sector based on biomass, producing alcohols and hydrogen (with carbon capture and storage);
- a transport system based on alcohols and hydrogen (with petroleum persisting for air transport);
- an electricity sector based predominantly on nuclear and renewables (other than biomass); and
- direct thermal needs supplied mainly by a combination of gas, hydrogen and additional electrification.

However, it is important to appreciate that this is not the only possible organisation of a future energy system compatible with longer-term sustainable development, although it is nonetheless a logical and consistent scenario. For example, the emergence of alternative energy conversion and fuel synthesis technologies may result in a substantially different development trajectory. Similarly, if some of the challenges associated with the specific technology options presented in this chapter prove to be insurmountable—such as large-scale mobilisation of biomass feedstocks—an alternative energy system development pathway will be unavoidable. We explore some of these potential alternative pathways in the following section, focusing on some factors likely to affect fuel production, including the potential impact of reduced biomass availability and alternative (i.e., additional) hydrogen synthesis technologies.

7.4.7 Alternative hydrogen synthesis pathways in sustainable development

As discussed in Section 7.4.4, one critical development identified as contributing to the emergence of a sustainable transport and energy system is the large-scale mobilisation of biomass for hydrogen and alcohol production. This development may be particularly challenging, however, given the large area of productive land that would need to be devoted to biomass production—particularly later in the century—under the scenario presented in this chapter. Realising other elements of sustainable development, including improving the long-term sustainability of agricultural activities, and maintaining biodiversity, represents a further challenge that may directly compete with the bioenergy requirements identified here.[83]

Accordingly, this section explores in more detail the possible role of two alternative hydrogen production technologies that do not suffer from the same potential limitations as biomass in achieving the goals of long-term sustainable development. However, these technologies—solar and nuclear thermal hydrogen production—are currently viewed as relatively experimental and immature, and for these reasons were excluded from the analysis presented in the preceding sections. Nevertheless, with rapid technological development these thermal synthesis pathways may become important alternatives to biomass-based hydrogen synthesis.

[83] In addition, biomass may become the preferred feedstock for the petrochemical industry over the century as cheap oil becomes increasingly scarce.

7.4.7.1 Advanced H_2 synthesis pathways

On this basis, this subsection explores the possible impact on fuel production of solar and nuclear thermal hydrogen production systems, assuming that these technologies become suitable for commercialisation and large-scale deployment during the 21st century. This is represented in the ERIS component of ECLIPSE with relatively optimistic estimates for the cost and performance of these technologies, taken from the database used with the MESSAGE model (Messner and Strubegger 1994; 1995; Totschnig 2006). For example, we have adopted estimates that result in production costs of around US$11/GJ for hydrogen from high-temperature nuclear reactors and US$15/GJ for solar thermal synthesis[84]—see Figure 7-15 for an illustrative comparison of fuel production (and transmission) costs for different fuel synthesis pathways in ERIS. However, to avoid being overly optimistic we assume in ERIS that nuclear high-temperature hydrogen production technologies become available only from 2030, and high-temperature solar technologies from 2050.

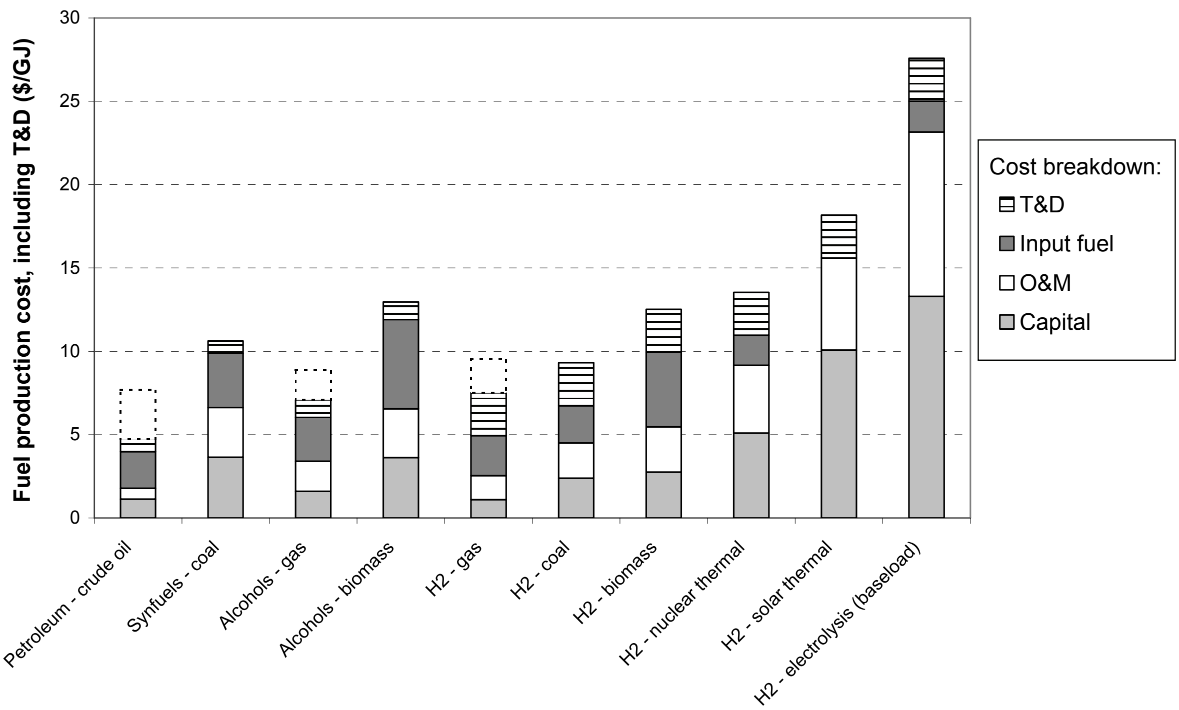


Figure 7-15 Illustrative production costs of different fuels (including transmission and distribution costs), North America (NAM)

Note: Calculated using technology floor costs—i.e., assuming maximum technology learning. Moreover, the cheapest domestic resources are assumed to be used as feedstocks, with the exception that the dotted region indicates additional costs from using the most expensive conventional category (IV) of oil and natural gas, from Rogner (1997). Production costs for hydrogen from electrolysis are calculated assuming very low base-load electricity costs of US$0.005 per kWh (equivalent to less than $2/GJ_{H2}$).

[84] Based on capital cost estimates of $2,200 and $2,900 per kW_{H2} for nuclear and solar technologies, respectively. The nuclear figures are consistent with some optimistic examples, such as in Schultz (2003).

Importantly, another potentially promising solar-based synthesis pathway, using solar reforming of natural gas (Moeller *et al.* 2006), is not explicitly included in the ERIS model. However, the characteristics of the thermal solar hydrogen technology mentioned above, and conventional reforming of natural gas incorporated in ERIS mean that solar reforming technology is implicitly included, with hydrogen production costs of around $9/GJ (with cheap natural gas).

Using otherwise identical assumptions and methodology, the ECLIPSE model was applied to construct a new sustainable development scenario incorporating these technologies—hereafter referred to as the "Advanced-H_2" scenario. The impact of including the additional hydrogen synthesis pathways on fuel production in the second half of the 21st century is presented in Figure 7-16. Figure 7-16 shows that under the Advanced-H_2 scenario total hydrogen production is significantly higher towards the end of the century (around 45 percent in 2100), which contributes to satisfying a slightly higher overall energy demand and economic output (not shown). One important factor enabling this additional hydrogen production is the attractiveness of nuclear thermal hydrogen synthesis technologies, which provide an additional source of competitive fuel.

It is important to remember, however, that we have applied optimistic assumptions for nuclear hydrogen technology. Furthermore, similar to the results presented in Section 7.4.6, nuclear technologies are deployed on a very large scale in electricity production under this new scenario. Given the scale and rate of this deployment, it may be challenging constructing the additional nuclear reactors needed for hydrogen production: this constraint is not modelled explicitly in the framework employed here, but we note that in the Advanced-H_2 scenario the nuclear thermal synthesis technology is deployed to the maximum allowed by other constraints assumed in the model.

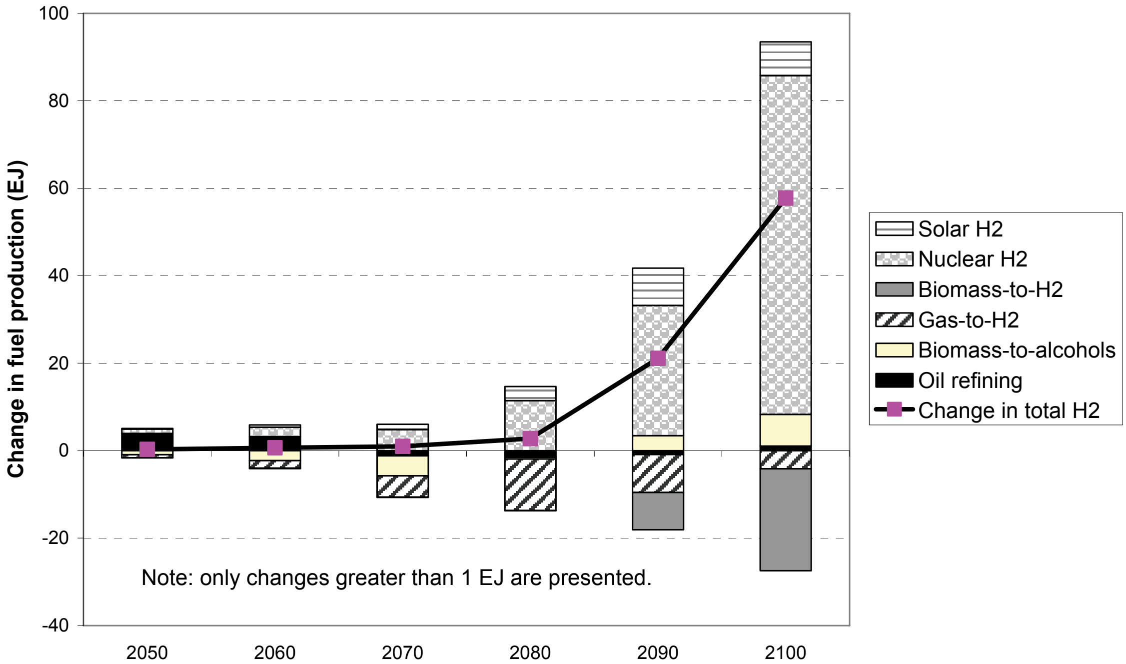


Figure 7-16 Impact on fuel production of availability of solar and nuclear thermal hydrogen production technologies, 2050-2100

Interestingly, the additional production of hydrogen with nuclear thermal technologies displaces only a relatively small amount of the hydrogen synthesised from biomass, peaking at around 20 percent in 2100, while hydrogen from natural gas reforming is reduced much more from 2070 to 2090 (see Figure 7-16). That is, nuclear synthesis pathways appear to be acting as a complement to biomass-based synthesis pathways, because hydrogen from these relatively abundant zero or negative emissions sources is a very attractive fuel given the sustainable development objectives of this scenario. Moreover, Figure 7-16 shows that some of the biomass displaced from hydrogen production is instead being used for additional alcohol production. Alcohol production is otherwise largely unaffected by the availability of additional hydrogen, indicating that this fuel may also act as a complement to hydrogen.

Compared to nuclear thermal synthesis, solar thermal hydrogen production is less attractive in the Advanced-H_2 scenario. The results presented in Figure 7-16 appear to indicate that this technology, although contributing around 10 EJ towards the end of the century, remains confined to smaller-scale applications compared to biomass- and nuclear-based hydrogen synthesis.

Accordingly, despite assuming that experimental solar and nuclear hydrogen synthesis pathways achieve commercialisation, production from biomass remains the main source of hydrogen under this sustainable development scenario. Biomass also remains an important feedstock for synthesis of alcohol fuels, with these fuels maintaining their importance in transport.

7.4.7.2 Advanced H_2 synthesis combined with reduced biomass availability

As discussed, however, competing demands for land may limit the availability of biomass for synthetic fuel production. Accordingly, we also analysed the impact of a reduction in biomass availability of 50 percent from 2050 to 2100.[85] The impact on fuel production compared to the Advanced-H_2 scenario presented above is shown in Figure 7-17. It should also be mentioned that very similar results were observed in an otherwise identical scenario where solar and nuclear thermal H_2 production technologies were excluded.

As expected, Figure 7-17 shows that synthetic hydrogen production from biomass is reduced under this alternative scenario, due to the assumed lower availability of feedstock. However, almost all of the reduction in hydrogen synthesis from biomass is compensated by greater production from solar and natural gas technologies.[86] In comparison, synthetic alcohol production from biomass is reduced by an even greater amount in all periods, and is not compensated by additional alcohol synthesis from other sources.

Accordingly, reduced biomass availability may, over the longer term, have a greater impact on alcohol production rather than hydrogen production from biomass. As a consequence, a more rapid shift to hydrogen may be necessary, due partly to the lower availability of alcohols as a transition fuel. This is illustrated for passenger car transport in Figure 7-18, which shows the change in market share for different drivetrain and fuel combinations under this reduced biomass scenario, compared to the Advanced-H_2 scenario. Figure 7-18 shows that FCVs become a more attractive option, while deployment of HEVs declines because, without

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[85] With availability reduced 10 percent in 2010, 20 percent in 2020, 30 percent in 2030 and 40 percent in 2040.

[86] Importantly, as mentioned in Section 7.4.7.1, nuclear hydrogen production technologies are already deployed at the maximum rate allowed by model constraints in the Advanced-H_2 scenario, and we do not allow higher deployment with the reduced biomass availability scenario presented here.

alcohol fuels, this technology becomes a less promising longer-term option for sustainable development.[87]

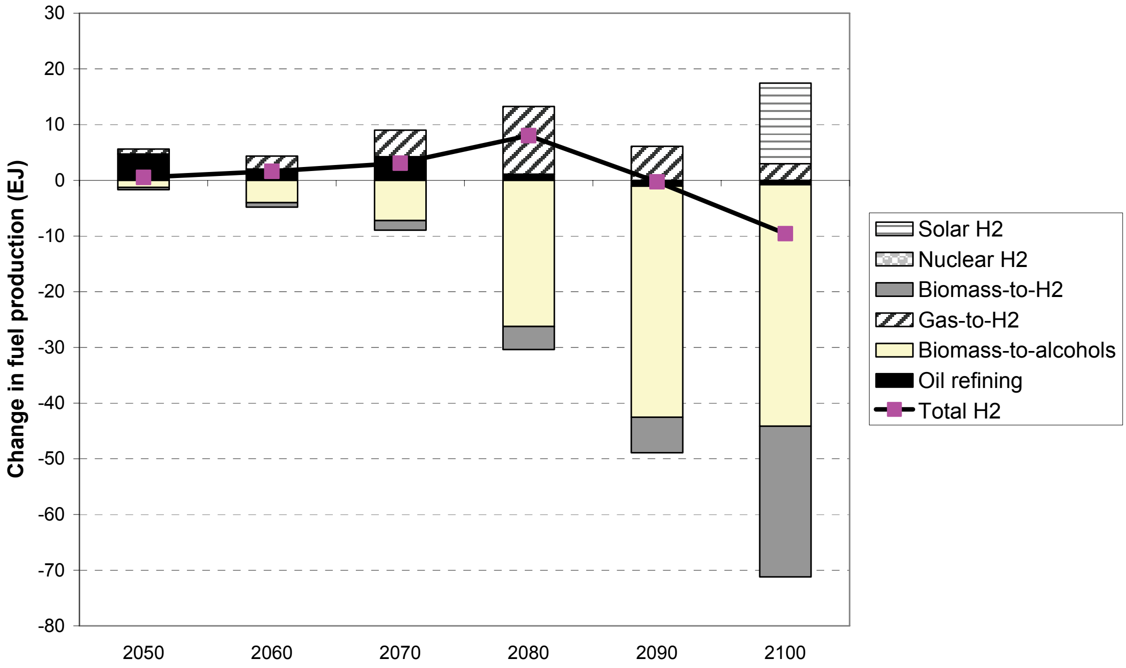

Figure 7-17 Impact on fuel production of reduced biomass availability compared to Advanced-H_2 scenario, 2050-2100

As mentioned earlier, one of the reasons that hydrogen synthesis from biomass remains an attractive option under this scenario is that it enables the production of a negative-emissions fuel (when combined with carbon capture and storage). The hydrogen produced in this way is a superior energy carrier for achieving climate change mitigation aspects of sustainable development.

To summarise, this analysis of alternative hydrogen production technology and biomass availability has illustrated some other possible energy system configurations compatible with longer-term sustainability. Importantly, the results presented in this section appear to confirm the key findings presented in the main analysis in this chapter, although some interesting additional insights related to deployment of advanced drivetrain technologies, and nuclear-thermal hydrogen production are outlined.

We now discuss in more detail some of the key developments required for the emergence of a sustainable transport system, and identify areas for public support or policy intervention.

[87] It should be remembered, however, that FCVs are modelled as FC-battery hybrids, as discussed in Section 3.3.3.4.

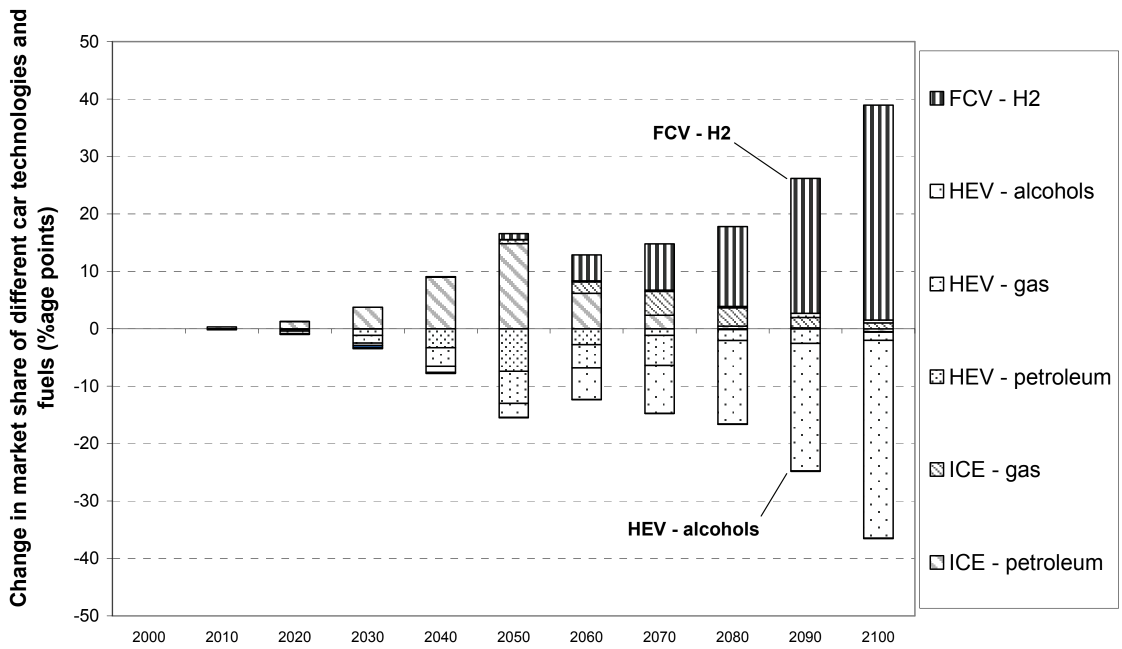

Figure 7-18 Impact on car transport technology and fuel use of reduced biomass availability, compared to Advanced-H_2 scenario, 2050-2100

Abbreviations are as follows: ICE—conventional internal combustion engine vehicle; HEV—hybrid ICE-electric vehicle; and FCV—hybrid fuel cell-electric vehicle.

7.5 Discussion: realising a sustainable transport system

The objective of the study presented in this chapter (and the second theme of this dissertation) is to firstly understand pathways to a sustainable global transport and energy system, and secondly, to identify key technological developments necessary for the emergence of such a system. By doing so, we seek to provide insights into key targets for public support, and identify areas requiring near-term intervention to shift the energy system's development trajectory onto a more sustainable pathway, particularly given the inertia of energy system development.

With these goals in mind, the scenario described in this chapter illustrates one pathway towards a global sustainable transport system, and describes in detail the energy and transport transitions along this pathway using an integrated modelling framework that includes energy system detail and interlinkages. However, a single scenario can only represent one configuration of the future, and significant social, economic, environmental, technological and political uncertainties mean that future developments are almost certain to follow an alternative pathway. Nonetheless, even a single scenario can provide a robust illustration of where, and the type of conditions under which, long-term challenges to sustainable development may emerge and the possible nature of these challenges. Moreover, the scenario presented here is based on drivers, including economic, institutional and technological, that are consistent with current and historical experience, and so may be well-suited to providing credible nearer-term policy insights for addressing longer-term challenges, despite future uncertainties.

7.5.1 Integrated framework

We have explored the emergence of a sustainable energy and transport system with an integrated modelling framework that includes a detailed bottom-up energy systems model with technological learning, a consumer-budget transport demand model, a top-down macroeconomic model and a climate model. Accordingly, the sustainable development scenario presented here incorporates important feedbacks between energy prices, energy demand and economic activity, while also capturing the potential impact of technological change on the transport system. In addition, the comprehensive energy model helps illustrate how all energy sectors develop towards sustainability in a consistent and complementary manner.

One key finding arising from the application of this framework is that a sustainable energy system can emerge over the long term at relatively little cost (roughly 2 percent of GDP by 2100). In addition, and more interestingly, these results imply that the higher per unit energy costs under a sustainable transport system may result in a shift from air transport towards additional automobile transport compared to an equivalent scenario where sustainable development objectives are not pursued, as consumers respond to higher prices by exploiting relatively cheaper transport modes. Importantly, this finding is based on the assumption that current institutional and economic drivers of transport demand (as discussed in Section 7.2.2) remain in place, and alternative modes such as high-speed railways do not significantly replace air or car transport.

However, there are a number of key uncertainties in this analysis including the pace and direction of technological change, the size of ultimately recoverable global oil and gas resources, and the required level of greenhouse gas abatement to avoid the worst impacts of climate change. If some of the technological developments envisaged here do not materialise, if more pessimistic assessments of global resources turn out to be accurate, or if more stringent abatement is required, then achieving the goals of sustainable development would require an even faster transition to new fuels and technologies than envisaged in the scenario presented here, probably at greater economic cost. Given that the scenario presented here already involves a number of radical changes to the energy and transport system, a faster and more extensive transformation poses further challenges and may require additional action to discourage certain transport modes and reduce the volume of transport and energy demand.

7.5.2 Transport technology transitions

Deployment of new technologies plays an important role in realising a sustainable transport system. In this scenario, in automobile transport there is initially an almost total transition from internal combustion engine vehicles to hybrid-electric vehicles, and eventually a shift towards hydrogen fuel cell vehicles.

Importantly, hybrid vehicles are already commercially available and have gained relatively widespread consumer acceptance, often supported by government initiatives (for example, tax deductions in the USA and grants and exemptions in the UK (IRS 2004; EST 2005)). However, HEVs still only account for a very small share of the passenger car market (with cumulative global sales over 8 years estimated to be below 1 million units), although this share is expected to grow rapidly.[88] The question remains whether current market drivers

[88] The leading suppliers of hybrid vehicles, Toyota and Honda, have sold over 500,000 and 100,000 hybrid vehicles worldwide, respectively (Toyota 2005; Honda 2005).

alone will be sufficient to promote a complete transition to these vehicles over the next 50 years or so. To ensure the full potential of this technology to contribute to sustainable development is realised there may be a role for public support to ensure economies of scale in production are achieved, and key barriers—such as battery costs and storage—can be overcome. Accordingly, there may be scope for government rebates, subsidies or procurement programs to create additional confidence in this technology.

Deployment of H_2 fuel cell vehicles is the other major technology development under this scenario. Although adoption is greatest later in the century, this only arises because of critical small-scale experience from as early as 2010 in heavy vehicles and 2020 in passenger vehicles. This early experience is essential for fostering technological improvements and cost reductions essential for later large-scale deployment. However, the immaturity and current high cost of fuel cells implies that market drivers alone will be unlikely to lead to socially optimal investment in this technology, highlighting the role for public support (Turton and Barreto 2005). This may involve R&D funding and co-ordination, government-sponsored demonstration and procurement programs, and support for deployment in specific niche markets—including in non-transport applications where improvements in the technology may lead to spillovers to transport. As this technology becomes more commercially viable, more demand-based support mechanisms, such as subsidies, rebates, standards and voluntary agreements will form an important complement.

In the context of the major technological transitions described in this scenario, it is worth restating that there exist significant uncertainties related to energy technology development, ultimately recoverable energy resources and other elements of the energy system. Although the analysis presented here covers in detail energy system interlinkages, we restrict this analysis to a realistic set of technologies, energy resources and market conditions to illustrate how a sustainable transport system can be realised without relying on highly unpredictable technology breakthroughs. Nonetheless, the possibility of such technology developments cannot be ruled out.

For example, one such revolutionary technology that is excluded is fuel cell vehicle-to-grid systems, where the fuel cell engines in stationary automobiles are used to provide electricity generation services, including for peak power and system stability (Kempton and Tomic 2005; Lipman *et al.* 2004; Letendre and Kempton 2002; Moura and Turton 2006; Turton and Moura 2006). These technologies still face a number of technical hurdles, but may potentially play an important role in the future. Importantly, support for fuel cell technologies also supports the possible emergence of these more radical energy systems.

7.5.3 Fuel production and other requirements

In addition to developments in transport technology, two complementary fuel production trends emerge in the sustainable transport scenario described here. The first is an increasingly important role of biomass as a primary feedstock, and the second, somewhat related, is the development of a hydrogen and alcohol-based energy system. Creating the production and distribution infrastructure required for large-scale deployment of these fuels poses a number of challenges.

In the case of alcohols some of these challenges may be relatively easily overcome, since alcohol fuels have some advantages in that they can be distributed using similar infrastructure to that employed for petroleum fuels. However, the emergence of a sustainable transport and energy system may well require the deployment of hydrogen-based technologies. To supply these technologies with fuel, it is likely that major capital-intensive investment in hydrogen production and distribution infrastructure will be necessary. Moreover, as is often cited, much of this infrastructure will need to be developed before there exists sufficient demand to make it commercially viable (Keith and Farrell 2003). However, because of the significant social benefits of sustainable development that may arise from H_2 deployment it is important that adequate investment is directed towards this infrastructure. This identifies an important role for public support, or innovative schemes to share the risk of large-scale capital-intensive infrastructure investment. Moreover, given the likely monopoly nature of a hydrogen distribution network, there exists an important role for government in overall strategic co-ordination of investment to guarantee an efficient network, in addition to more traditional roles in regulation.

In the sustainable transport scenario presented here, both alcohols and hydrogen are synthesised predominantly from biomass. This is despite the fact that creating an energy system in which biomass is one of the main primary feedstocks poses a number of significant challenges. Biomass is favoured because without major technological breakthroughs—for example, that result in a large surplus of cheap renewable energy for large-scale electrolysis, breakthroughs in solar thermal (or thermochemical) hydrogen production, or very large-scale carbon capture and storage—there are relatively few long-term cost-effective alternatives to biomass for transport fuel synthesis. One further possibility examined here that may have some potential is hydrogen produced from high-temperature nuclear reactors (for example, see DOE 2002), although this is a relatively experimental technology and nuclear energy is already heavily exploited for electricity generation in this scenario suggesting there may be limited scope for further applications.

Nevertheless, even if some of the breakthrough technologies mentioned above emerge, biomass-based H_2 production systems may continue to be superior in terms of CO_2 emissions. This is because sustainable biomass production combined with carbon capture and storage in H_2 synthesis leads to a fuel with net negative emissions, whereas most other alternatives can at best achieve zero emissions.

The challenges facing large-scale sustainable biomass mobilisation relate particularly to finding sufficient productive land to devote to fuel production, while satisfying increasing human needs for food and fibre, and at very least *maintaining* environmental amenity. The scale of biomass production is best illustrated by considering that the resource potential identified by Rogner (2000) (and used here) was based on the availability of an additional 1.3 billion hectares of land globally. Clearly, biomass production on a scale of this order of magnitude must address other aspects of sustainable development, including effective water and soil management, nutrient recycling and preservation of organic matter (Reijnders 2005). In addition to a significant transformation to land management systems, and utilisation of all organic waste streams, sustainable biomass production faces other challenges. Harvesting and transporting biomass to fuel synthesis plants represents a significant logistical challenge, although this may promote smaller-scale decentralised alcohol and hydrogen synthesis close to the feedstock source. Such decentralisation, however, may merely shift logistical difficulties further down the production chain. On the other hand, there may also be benefits compared to today's relatively centralised oil industry because fuel production and demand centres may be proximate (compared to today's oil industry which relies on long-distance transport), and the fuel production system will no longer necessarily depend on a small number of large critical infrastructures—such as pipelines, shipping terminals and refineries—but instead on a less vulnerable network of energy producers.

However, developing such a sustainable biomass-based energy production system is likely to require a long-term overall strategic vision and substantial investment, and face long lead-times before becoming profitable. This highlights the need for innovative approaches to investment, including public-private partnerships (for example, see PCAST 1999), and a role for governments in providing the strategic framework in which private sector expertise can be exploited to realise long-term social goals, whilst ensuring other aspects of sustainability are addressed. Moreover, the major transformations to the energy and complementary systems described here may be particularly challenging in the developing world, where many of the systems may need to be established from scratch. Accordingly, realising long-term sustainability is likely to also require major international partnerships to promote technology transfer and investment in new energy, transport and supporting system infrastructure.

7.5.4 Market drivers

Achieving the technology and fuel production requirements discussed above involves overcoming both technical and market barriers. So far we have focused predominantly on technology-specific measures, but there is also a strong case for the application of broader-based policy instruments to encourage a transition to a more sustainable energy system such as that envisioned in this chapter. These may include taxes and tradable permit schemes, although alone these measures would need to be fairly stringent and costly to achieve the required technology transition. However, they can still play an important role even at low levels initially by discouraging those technologies and fuels least compatible with sustainable development, and by creating market conditions that lower the commercial barriers to the adoption of new sustainable technologies.

7.5.5 Climate change and security of supply

As a final point, we have presented in this analysis a scenario in which two major challenges to sustainable development—climate change mitigation and maintaining security of energy supply—are confronted and managed to reduce long-term risks. Importantly, there are synergies between these two policy goals when pursued together—illustrated best perhaps in the scenario presented here by the deployment of alternative fuels such as alcohols and hydrogen that can help achieve both policy goals. However, as shown by Turton and Barreto (2006) and in Chapter 5, it is important to appreciate that these synergies may not be realised cost-effectively if one policy goal is pursued whilst ignoring the other. Such an approach runs the risk of locking the energy system onto a development trajectory that may be incompatible with uncertain future challenges. This highlights the need for a long-term strategy to incorporate multiple policy objectives, and consistent with this requirement, we have presented and analysed here a scenario that integrates a number of elements of long-term sustainable development.

7.6 Conclusions

The sustainable transport scenario presented in this chapter represents the culmination of the work presented in the preceding chapters. The methodological developments and elements of sustainability explored in these earlier chapters are synthesised in this present analysis to illustrate one possible configuration of a future global energy system that restricts atmospheric CO_2 concentrations to below 550 ppmv, maintains resource-to-production ratios for oil and gas above 40 years, and satisfies a rapidly growing global demand for transport, all at a cost of around 2 percent of GDP by 2100. Moreover, this scenario helps elucidate the possible pathways along which a sustainable transport system may emerge, and begins to lay out a technological and infrastructure roadmap illustrating one pathway, including key challenges. In doing so we identify critical roles for hybrid-electric and fuel cell technologies, and alcohol and hydrogen fuels synthesised from biomass, all of which may be potential candidates for strategic public support and coordination of private investment. This highlights the potential importance of innovation, both in terms of technology and policy support, in a transition to sustainability. Given the slow rates at which energy and transport infrastructure develops, and the need for a major transformation of the energy system indicated in this analysis, the results in this chapter provide further support to the notion that early and consistent action is necessary to achieve sustainable mobility. Furthermore, because the scenario presented here is based on many current trends and institutional drivers it may provide credible nearer-term insights for today's policymakers, despite substantial future uncertainties.

Chapter 8. Summary and conclusions

This dissertation has attempted to address two main objectives and related themes throughout. The first objective was to develop a comprehensive, yet flexible, scenario and policy analysis tool to assist the identification of potential challenges to sustainable development, and support the formulation of appropriate policy responses. This was motivated by the fact that realising the goals of sustainable development represents a significant challenge confronting a range of decision makers throughout the world, and effective tools are required.

The elements of sustainable development that this dissertation has focused on are those most relevant to the energy system, particularly in terms of the impact of the energy system on climate change, threats to access to secure supplies of energy, and the need to mobilise energy resources and investment sufficient to achieve economic and social development goals. Other aspects of energy sustainability, although not explicitly covered here, that are also important relate to factors such as local and regional pollution and potential and perceived risks of nuclear power.

The analysis tool described herein was constructed to address many of the key elements of sustainable development outlined above. One specific challenge to sustainable development which is addressed in detail is that emerging in the transport sector, where increasing incomes are anticipated to drive major increases in private travel demand, and hence energy use and greenhouse gas emissions. Moreover, since transport is highly dependent on petroleum fuels, future transport demand may represent a major source of energy insecurity. Accordingly, the second main objective of this dissertation was to study the potential role of new automobile technologies and fuels in sustainable development, including the possible emergence of a sustainable transport system. This also warranted a more detailed analysis of potential synergies and trade-offs between competing aspects of sustainable development—specifically, climate change mitigation and security of the energy supply.

The remainder of this chapter presents a summary and the main conclusions of the two main themes dealt with in this dissertation.

8.1 The ECLIPSE policy analysis tool

Decision-makers in governments around the world are confronted by an array of complex challenges as they endeavour to predict the impact of existing and prospective policies on future social, economic and environmental well-being. Among the challenges facing policy-makers this century, the most significant may relate to realising the goals of sustainable development, whereby current needs are met without compromising the ability of future generations to meet their own needs.

Accordingly, as mentioned above, one of the main aims of this dissertation has been to construct a comprehensive and flexible global policy analysis tool for investigating the impact of future scenarios and policy measures on sustainable development, including on indicators of climate change (such as global average temperature, sea-level), energy and transport system characteristics and economic variables.

8.1.1 Model development

Given this interest in energy and sustainability, the first step in developing this policy analysis tool was to construct a comprehensive and detailed model representing the global energy system, from fuel resources, to conversion technologies, to transmission and distribution infrastructure, through to end-use activities. This was achieved by substantially expanding the ERIS (Energy Research and Investment Strategies) model as described in Chapter 3, which ensures that interactions, competing technologies, and competing demands within the energy system are addressed in a suitable level of detail to provide insights allowing the identification of fuels and technologies compatible with sustainable development. In addition, given the second theme of this dissertation, the policy analysis tool also incorporates additional technological detail for private passenger transport, covering a range of technology-fuel combinations for automobile travel.

Moreover, given the historical importance of technological transitions in energy system development, the policy analysis tool also incorporates two key features of technological change. These include technology learning, whereby technology costs decrease as a consequence of experience in making and using a technology, and the effect of clusters, whereby compatible technologies and systems can lock in a particular technology and protect it from competitors. Within the policy analytical framework described in this dissertation the representation of technology clusters arises mainly as a by-product of the level of energy system detail. However, sub-clusters involving technologies which rely on similar key components are modelled explicitly.

The inclusion of technological change in the policy analysis tool is particularly important for exploring future development of the transport sector because a number of potentially attractive technologies and fuels are currently immature and expensive. Moreover, some of the more advanced technology options represent a major departure from the current internal combustion engine (ICE)-petroleum technology cluster (or paradigm). The ability to account for potential benefits from and barriers to technology diffusion is important for understanding possible long-term changes.

In addition to incorporating a detailed model of the energy and transport system, the policy analysis framework described in this dissertation includes a number of other important features. The first is a linkage to an economic production model, representing non-energy economic activities and demand for multiple sources of energy and energy services. This so-called ‘top-down’ economic model is an ideal complement to the ‘bottom-up’ energy systems model mentioned above, and described in detail in Chapter 3. Specifically, it helps overcome a potential weakness of bottom-up energy systems models which, although rich in technology detail, provide little indication of broader economic implications of following alternative energy system development pathways. Moreover, technology-rich bottom-up models also often implicitly apply the counter-factual assumption that energy demands are completely inelastic to changes in energy prices. Accordingly, the addition of an economic model to the overall policy analysis framework enables the analysis tool constructed in this dissertation to provide more realistic and intuitive insights to policy-makes, which at very least enhances the credibility of the analytical results obtained.

The economic model, which is described in detail in Chapter 6, combines elements from a number of earlier approaches to linking top-down and bottom-up models, and goes further by including four separate energy-service markets (or production inputs), comprising electric energy, heat, high-quality thermal energy and freight transport. This model seeks to represent how these inputs are combined with capital and labour to create economic output, and accounts for possible substitution between energy, capital and labour.

It is important to emphasise, however, that unlike earlier approaches, passenger transport demand is excluded as an input to economic production in the model described above on the basis that private mobility is a consumption good, rather than an input to production. Accordingly, a separate model of long-term passenger transport was developed based on consumer travel time and money budgets.

The transport model seeks to represent the preference of consumers for convenient and faster modes of transport, based on the concept that people are willing to devote only a limited amount of time to travel. This same principal was applied in constructing the scenarios of future transport demand used throughout the analyses presented here, and described in Section 3.2.2 of Chapter 3. In the transport model, the combination of limited travel money budgets and limited time budgets means that changes in the price of different transport modes results in substitution between modes and changes in total demand. As a consequence, a particularly interesting result was observed: that efforts to achieve some of the elements of sustainable development may have the consequence of shifting passenger travel demand away from air transport back to private automobile transport. Although air travel represents a potentially highly unsustainable form of transport, and in overall terms a net shift to automobile travel may be a positive development, it may nonetheless counteract policies promoting sustainable automobile transport, particularly in terms of congestion and local air pollution. This identifies a particularly important role for governments in promoting alternative long-distance passenger transport modes, such as high-speed trains. This result was presented in Chapter 6 and Chapter 7.

The paragraphs above have sought to recapitulate briefly how the policy analysis tool developed in this dissertation combines models representing energy and transport system detail and dynamics, economic activity and transport demand, and the benefits of this combination. These benefits include, for example, providing the means by which to analyse elements of sustainable development, including economic development and features of the energy system, including security of energy supply. To further facilitate analysis of other aspects of sustainable development, the above framework was also linked to the MAGICC climate change model (Hulme *et al.* 2000).

Importantly, to fully exploit the features of the climate model, it was necessary to extend and the energy system model to include emissions from sources other than fuel combustion. The model extensions include the addition of upstream emissions in energy production, emissions from cement and other industrial activities, and emissions from waste and agriculture. Importantly, the non-energy emissions are not represented with the same level of technology detail as the energy and transport sectors, as described in Chapter 3. However, given the purpose of linking the climate model to the policy analysis framework is to enable assessment of climate change mitigation strategies, it was necessary to include abatement options for all sectors, also including land-use change and forestry. Accordingly, for non-energy emissions, stylised marginal abatement cost curves were included, as discussed in Section 3.3.7 in Chapter 3. In addition, detailed technologies were included for carbon dioxide capture from energy activities, and subsequent storage.

The above combination of features—covering energy, transport, technological change, economic activity, GHG abatement and climate change impacts—included in the policy analysis tool provide a means to measure and report multiple indicators of sustainable development, covering economic development, climate change, energy and technology detail, and energy security. Accordingly, this analytical tool—called ECLIPSE (Energy and Climate Policy and Scenario Evaluation)—represents the realisation of the first objective of this dissertation. The main elements of the ECLIPSE analysis framework are illustrated schematically in Figure 8-1.

8.1.2 Scenario development

The second aim of this dissertation was to apply this analytical framework to explore the emergence of a sustainable automobile transport system over the long term. For this purpose, and for exploring different aspects of sustainable development and transport technology choice during the construction of the analysis framework, a future global scenario was constructed.

The specific scenario was selected so as to facilitate an analysis of the possible reconciliation of competing objectives of sustainable development. Throughout this dissertation we used the Intergovernmental Panel on Climate Change's SRES B2 scenario (Riahi and Roehrl 2000) as a starting point, given that it represents a 'dynamics as usual' future scenario of socioeconomic development not inconsistent with sustainable development. Moreover, B2 was selected because it is based on a continuation of many historical drivers and institutions, making it intuitively plausible and credible to today's policymakers.

Some of the other features of this scenario that make it suitable for exploring possible sustainable development pathways include its long timeframe (to 2100), which is required to represent the period across which many future challenges to sustainable development are likely to emerge, particularly in today's developing world regions. Moreover, this timeframe is necessary to study the possible long-term technological changes required to shift the global energy and transport systems onto a more sustainable trajectory, given the high inertia arising from the slow turnover of long-lived infrastructure and the long periods required to shift from today's dominant technology clusters (see Section 2.2 in Chapter 2 for a more detailed discussion of clusters). Another element of the B2 SRES scenario that makes it suitable for studying various aspects of sustainable development is that it is available on a reasonably disaggregated level of regional detail. This is particularly important for examining the impact of energy resource availability on development, and energy security.

However, SRES B2 was only taken as a starting point and the purpose of this analysis was not to emulate this scenario. Accordingly, a number of important changes were made, the most significant of which relates to passenger transport demand. These changes were necessary because transport is generally treated in aggregate and in a stylised way in the SRES, making it unsuitable for exploring sustainable automobility in detail. Furthermore, the B2 scenario applied the fairly optimistic assumption that a world with low car dependence would emerge. Given that this assumption is somewhat inconsistent with other elements of the B2 scenario, in which current institutions and drivers (which have led to car dependence in many parts of the world) remain among the dominant forces in the future, an alternative transport scenario was developed. This transport scenario is described in Chapter 3, and incorporates a combination of current trends, estimates of plausible saturation levels for automobile adoption, and the impact of travel time and future money budgets in different world regions.

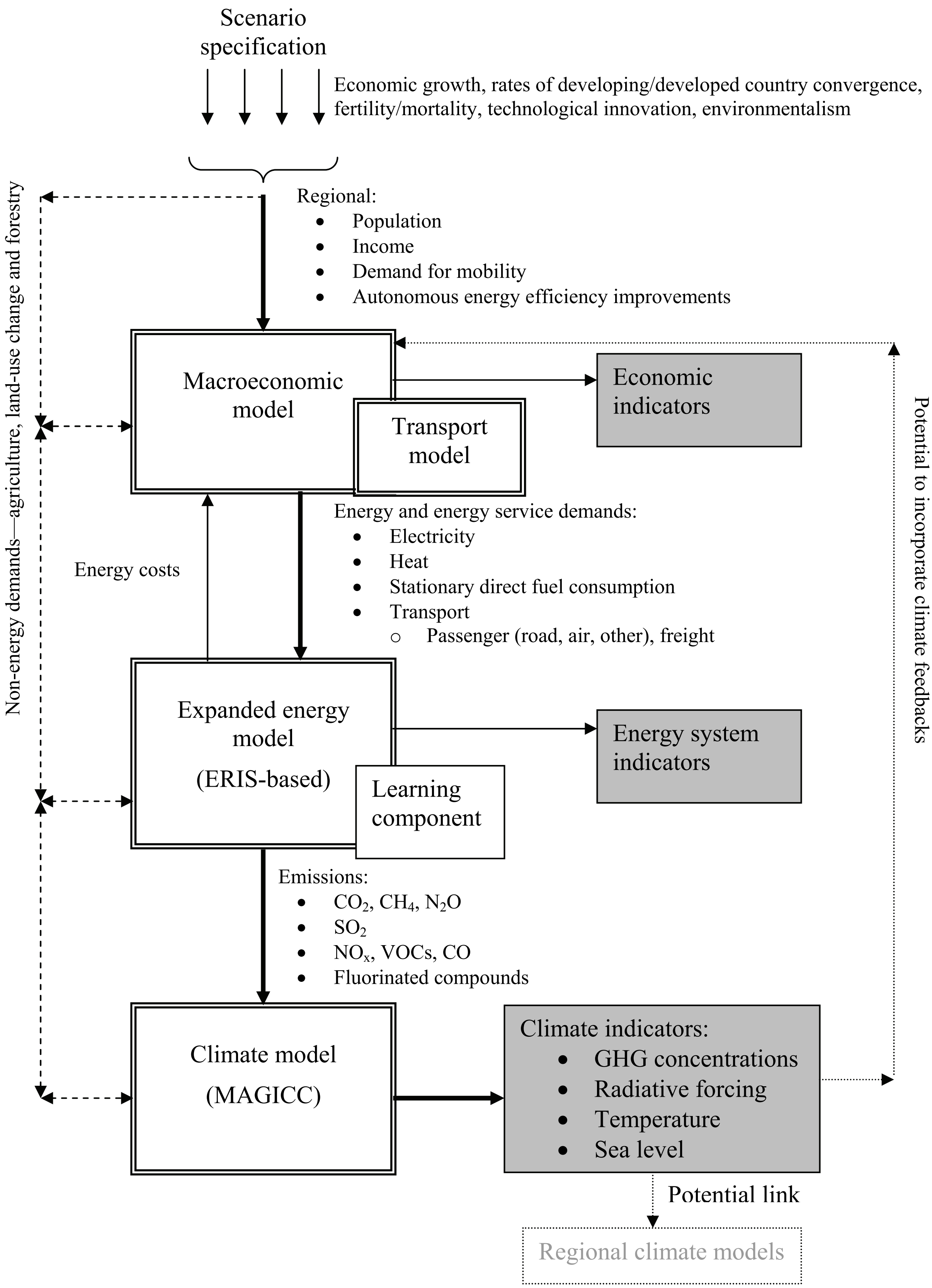

Figure 8-1 Structure of the ECLIPSE sustainable development and policy analysis tool

8.1.3 Synergies among sustainable development objectives

During the development of the ECLIPSE model a number of test analyses were performed using this scenario, including: an analysis of vehicle technology deployment under a range of greenhouse gas abatement policies; an analysis of synergies and trade-offs between policies aimed at maintaining a secure energy supply and those concerned with climate change mitigation; and an analysis of the economic and energy system implications of achieving alternative atmospheric carbon dioxide concentration targets (presented in Chapters 4, 5 and 6, respectively). These analyses contributed to both themes of this dissertation, although the studies on vehicle technologies and energy system implications of climate change mitigation are discussed in more detail in Section 8.2 below in the context of realising a sustainable passenger transport system. Although security of energy supply is also incorporated in the overall results reported below, additional and broader insights were derived in the analysis presented in Chapter 5 regarding the nature of synergies between climate change mitigation and long-term security of the energy supply, and we turn to these briefly.

Specifically, it was observed that the interactions, synergies and trade-offs between policies directed at these two elements of sustainable development are complex and depend on, among other things, the stringency of the greenhouse gas abatement regime—with more stringent mitigation efforts contributing significantly to improved oil security and diversification of the energy mix, including towards hydrogen. Nonetheless, synergies were also observed between less stringent mitigation policies and long-term energy security policies.

The analysis of synergies between energy security and climate change was extended further in Chapter 5 to exploit the technological detail in the ERIS model (which forms a key part of the ECLIPSE framework), by examining the impact of technology policy support policies—in this case deployment and demonstration policies—in achieving either mitigation or security objectives more cost-effectively. An important finding of this analysis was that although such policies can reduce the costs of achieving the goals of sustainable energy system development, if technology support is pursued within a broader policy context that addresses mitigation only, or energy security only, there is a risk of locking the development of the energy system onto a pathway from which it is more difficult (costly) to achieve other objectives of sustainable development.

This highlights the type of analysis of sustainable development for which the ECLIPSE framework is suitable—combining technology, climate change and energy security. However, the focus of this dissertation is on a more specific aspect of sustainable development, and we now turn to the main conclusions from the application of the analytical framework to explore the possible emergence of a sustainable automobile transport system.

8.2 Technology roadmap to sustainable automobile transport

The second main theme of this dissertation was to explore the possible emergence of a sustainable passenger transport system, focusing particularly on whether future demand for private automobile travel can be satisfied in a way that is consistent with long-term sustainability. The analysis of these issues encompassed both specific investigation of passenger transport, and a broader exploration of how the entire global energy system can develop in a way that provides energy needed for socioeconomic development and mobility while limiting the possible impacts of anthropogenic climate change and maintaining long-term security of the energy supply.

The analyses in this dissertation, particularly those in Chapter 4 and Chapter 7, identified a number of features of a future sustainable automobile transport system. These features include the adoption of specific transport technologies and fuels, along with other energy system developments. Before turning to these below, it is important to recall that only a limited subset of future scenarios were explored in the analysis of sustainable transport presented here, despite large uncertainties regarding future economic, social, political and technological developments. Nonetheless, one should also remember that the future scenario explored in this dissertation was selected because it appears plausible and is consistent with historical experience. The largest potential advantage of this scenario is that it appears credible in the context of current global institutions and many historical developments, and hence may provide nearer-term insights that are consistent with the perspectives of today's policymakers. This is advantageous in terms of motivating appropriate near-term responses to longer-term challenges, despite future uncertainties.

Nonetheless, other future trajectories of socioeconomic development are also possible. For this reason, the specific future energy and transport technology pathways identified in this dissertation should be seen as providing broad guidance regarding the type and possible timing of particular transitions, rather than specific indications of ideal technology market shares and adoption strategies in different world regions. In addition to this important caveat, it should also be recognised that we have not considered possible unforeseen events; on the positive side including developments such as technological breakthroughs, and on the negative side possible socioeconomic disruptions, such as conflicts or recessions. Historical experience suggests that neither can be discounted.

8.2.1 Vehicle technologies

We now turn to the specific technology, transport and energy system developments identified in this dissertation as characteristic of sustainable automobility. One of the main findings was that hybrid ICE-electric vehicles (HEVs) and fuel cell vehicles (FCVs) are both likely to play an important role in any future transport system—particularly where sustainable development is an objective, as presented in Chapter 7 and Chapter 4. However, the timing of these two transport technology options varies depending on a number of factors. HEVs appear to be an attractive early and mid-term option in almost all cases, since they can be diffused into the market relatively rapidly due to their ability to exploit existing fuel production and distribution networks. The introduction of HEVs can be considered an incremental rather than a radical technological change.

Over the medium term, HEVs fueled with natural gas and alcohol fuels may represent an important technology transition on the pathway towards sustainable development. HEVs powered by natural gas were identified as a potentially attractive combination in a number of analyses presented in this dissertation. This combination not only results in significantly lower greenhouse gas emissions compared to conventional ICE engines fueled with petroleum fuels, but also contributes to security of energy supply by diversifying the transport fuel mix towards a more abundant fuel with a different geographical distribution (see Sections 5.2.1 and 5.4.2.1 in Chapter 5). That is, this option appears to have economic, environmental and security benefits, while still relying on largely conventional fuel for which much infrastructure already exists in many parts of the world.

HEVs powered by alcohol fuels represent perhaps a further incremental step towards a sustainable transport system. Alcohol fuels are already important in some regions of the world and have particular advantages that they can be produced from renewable fuels and handled relatively easily. Accordingly, the HEV-alcohol combination represents one potential technology cluster consistent with sustainable development, and may particularly suited to parts of the world with abundant feedstocks for alcohol production are available, and where barriers to alternative sustainable automobile transport options—such as FCVs—may be larger.

Turning now to FCVs, this technology represents a much more radical departure from the existing transport and fuel technology cluster—ICEs and petroleum—and thus faces significantly larger barriers. The analysis in Chapter 4 showed, for example, that FCVs may remain largely unattractive without stringent policies promoting sustainable development, in this case climate change mitigation. Although the analysis in this dissertation also suggests that FCVs on their own represent an expensive abatement option, the scale of the challenge of sustainable development (including the required abatement to avoid dangerous climate change, and other elements such as maintaining energy security, and reducing urban pollution) appears to warrant support for the deployment of this technology, as illustrated in the analysis presented in Chapter 7.

However, the successful diffusion of FCVs, thereby opening up additional options for improving energy security and mitigating climate change, is more easily achieved if the technology is provided with opportunities to benefit from early experience, perhaps in niche markets. This early experience was seen to be critical not only in reducing costs of FCVs by learning by doing (see Section 3.3.6 in Chapter 3), but also for stimulating other energy system developments, including the development of a new production and distribution system for hydrogen (H_2). Importantly, direct H_2 FCVs were identified as the most attractive of the FCV options in this dissertation, given their lower cost and complexity, and higher efficiency than reformer-based alcohol- or petroleum-fueled FCVs.

It should be noted that all of the transport technology options identified in this dissertation as potentially necessary for realising a sustainable transport system have a number of features in common. However, perhaps the most important two are improved efficiency and fuel switching. Each of these features is important for sustainable development: efficiency reduces fuel use and hence contributes to greenhouse gas abatement, supply security, and the provision of affordable energy services for development; while fuel switching diversifies the fuel mix, contributing to energy security and, in the case of the fuels identified as most attractive, reduces greenhouse gas emissions. Accordingly, new transport technologies represent an important opportunity to realise synergies between different and potentially competing elements of sustainable development—such as climate change mitigation and security of supply. Other potential synergies were explored in Chapter 5, but one of the most important identified was a significantly increased attractiveness of hydrogen when multiple sustainable development objectives, or stringent criteria, were being pursued. We return to this below.

Given the different stages of development and deployment of HEVs and FCVs, and their potential role in long-term sustainability, different support strategies appear appropriate. In the case HEVs, with most technical barriers already overcome, the most effective public support mechanisms probably relate to creating suitable market conditions. That is, measures such as vehicle standards and taxation, public procurement programs, and capacity-building in domestic ancillary industries (e.g., vehicle maintenance services) may represent some of the more appropriate forms of public support for fostering a steady transition towards a more sustainable automobile transport sector. Most of these measures are focussed on eliminating market barriers, or ensuring market prices better reflect social costs and benefits.

FCVs face a different set of challenges, and although long-term market signals may be important, additional support is required in overcoming remaining technical barriers, and supporting early applications in niche markets. Accordingly, research and development (R&D) incentives, support for demonstration programs, and eventually direct procurement may be more important. In this context, readers should recall that FCV automobiles may not initially be the most attractive market for deployment of hydrogen transport technologies (as discussed in Chapter 4). Applications in heavy vehicles may initially be more competitive because there are fewer constraints related to on-board fuel storage, and a less diffuse refueling infrastructure is required. Such vehicles may represent an important early niche market for experimenting with FC technologies. In the longer term, however, to achieve a significant level of diffusion the FCV technology requires additional complementary systems in fuel production and distribution, which are discussed below.

Importantly, the analysis presented in this dissertation shows that both the incremental route towards a more sustainable transport system via HEVs and the more radical route via FCVs should be pursued. Such an approach represents a means by which to manage technological, economic and environmental risks, given the possible emergence of unforeseen technical barriers to either sustainable technology option, and the scientific uncertainty regarding the possible need for a more rapid shift to sustainability.

8.2.2 Fuel choice, production and distribution

Irrespective of the technology that emerges as the most suitable for sustainable automobile transport, one consistent finding of this analysis is that petroleum fuels appear unable to satisfy future transport demand in a way the supports energy security or greenhouse gas abatement. Three main transport fuel transitions were observed to be important for sustainable development. The first of these was briefly mentioned above, and comprises a shift towards natural gas. Natural gas is a more abundant fuel, and greater use in transport diversifies the energy supply (including geographically) and helps reduce greenhouse gas emissions, given gas's lower carbon content relative to petroleum. Moreover, the existence today of gas transmission and distribution systems in many parts of the world mean that some of the potential infrastructure and investment barriers associated with a shift to natural gas in transport are relatively easily surmounted.

The second important fuel transition observed over the medium term is a shift to alcohol fuels synthesised from biomass. Alcohols are already an important fuel in some world regions, notably Latin America, and such a transition could be expected to occur most rapidly where abundant biomass is available, or dependence on imported fuels is particularly high. As with natural gas, a shift to alcohol fuels further diversifies the fuel mix, and in many cases may allow a much larger share of transport energy needs to be supplied from indigenous resources. The availability of dual-fuel vehicle technologies that can utilise almost any mixture of alcohols and petroleum may represent an important technology for fully exploiting the benefits of a more diversified fuel mix. Moreover, alcohol fuels produced from sustainably harvested biomass result in essentially zero net greenhouse gas emissions, so a shift to these fuels represents a further step towards sustainability.

Importantly, however, there are a number of significant challenges to large-scale production of alcohol (or other fuels) from biomass. One of the most important considerations in the context of sustainable development is whether there is sufficient productive land available for growing biomass for alcohols, given competing demands for food and fibre production and environmental protection. Moreover, to fully realise the benefits of sustainable development, biomass produced for energy needs to be truly sustainable, with appropriate land and nutrient management and support for biodiversity. It is also important to note that the large land area required for large-scale energy production from biomass also implies a much more decentralised system of fuel production.

Many of these issues are also highly relevant for production of hydrogen (H_2), which represents the final stage of the three fuel transitions identified in this dissertation. Although hydrogen production from other primary fuels, such as natural gas or coal, may represent an important intermediate stage in the emergence of a hydrogen-based transport system, the results of the analysis described in this dissertation suggests that the most desirable option for sustainable development is H_2 from biomass, unless there are technological breakthroughs in alternative synthesis pathways, such as nuclear and solar thermal-based production technologies. Accordingly, establishing a large-scale alcohol-from-biomass production system, as described above, including the associated management, institutions and infrastructure, can be viewed as an important element in a transition towards large-scale H_2 synthesis from biomass.

Such a shift to fuel production from biomass can be viewed as a radical departure from today's energy production and distribution paradigm, which is organised around large-scale and highly centralised facilities. The most significant challenges associated with a transition to a decentralised biomass fuel production system are likely to be related to logistics and transport, and similar challenges are likely to apply to other renewable-based alternatives such as solar thermal hydrogen production. However, as discussed in Chapter 7 this may have some advantages in terms of more closely locating fuel production with demand centres, and avoiding over-reliance on single critical pieces of infrastructure. The associated potential energy security benefits are in addition to those arising from diversification of the fuel mix away from dependence on petroleum fuels for transport. The analysis in Chapter 5 indicates that hydrogen is potentially important for managing simultaneously the risks of climate change and energy security, since it can spread dependence across a number primary fuels, including those sourced domestically (such as biomass). In addition, in both this analysis and that in Chapter 4, support for hydrogen was identified as a hedging strategy against unforeseen and emerging risks, including the possible need to adopt aggressive greenhouse gas abatement policies, since it increases energy system flexibility and may create additional mitigation opportunities.

In the case of hydrogen from biomass, one of the most significant advantages for long-term sustainable development is the opportunity to produce a fuel with net negative emissions by combining sustainable biomass production with carbon capture and geological storage during hydrogen synthesis. The main trade-offs, as discussed above, are potentially higher distribution costs and the need to develop an entirely new fuel infrastructure, which represents a substantial barrier.

Accelerating the three fuel transitions discussed above represent perhaps a more daunting challenge than promoting the diffusion of HEVs and FCVs. The importance of biomass as a feedstock for either alcohol or hydrogen production clearly identifies a need to provide long-term incentives for establishing sustainable biomass agricultural systems. Given the importance of realising other goals of sustainable development, in terms of biodiversity and sustainable land management, large-scale biomass-for-energy production may require a longer investment cycle than conventional plantations or crops. This identifies a possible role for government support in providing investment support, such as through loan guarantees or other instruments. Moreover, policy makers may need to play an important role in promoting land (and biomass waste) management practices consistent with sustainable development, such as through standards or certification programs for energy biomass.

The second major area for potential public support in promoting the transport fuel transitions compatible with sustainable development relates to transmission and distribution infrastructure. In the case of alcohol fuels, similar infrastructure and systems used for petroleum fuel distribution may be suitable, and the most suitable target for public intervention may be in fostering market demand for these fuels, such as through performance or fuel mix standards. By contrast, the need for specific technology support may be more pressing in the case of hydrogen, where establishing a transmission and distribution network is likely to be very costly. Moreover, at the time when the initial investments in a H_2 transmission and distribution network need to be made, hydrogen demand will probably be small, potentially rendering investment in this infrastructure commercially risky. This identifies an important role for public support, given the potential benefits of a transition to hydrogen over the longer term, and governments may need to undertake partnerships with the private sector to help manage the risk of investment in long-term energy infrastructure that represents a major shift from the prevailing fossil-fuel paradigm. This support may include promoting end-use fuel-switching to hydrogen, perhaps initially in large stationary applications where infrastructure costs are minimised and can be amortised over a larger average demand. In addition to supporting investment and initial niche markets, governments will also need to play a more traditional regulatory role. This is because, as discussed in Chapter 7 fuel delivery infrastructure, particularly in the case of hydrogen, is likely to be a monopoly asset, necessitating also a strong public involvement in co-ordinating and overall planning of an efficient network.

Although much of the above discussion on possible effective public support options for more sustainable transport fuels has focussed on the more radical changes associated with implementing a biomass-based transport energy system, it is important to also reiterate that earlier in the 21st century achieving a greater penetration of natural gas into the transport market may be important for sustainable development (and this may apply also to synthetic natural gas alternatives). In many parts of the world, particularly in industrialised countries, natural gas infrastructure is already well developed. In these cases, demand-pull policy measures may be the most effective means by which to promote greater use of this fuel in transport. Suitable policy instruments may include greenhouse gas emissions standards, and taxation regimes (for fuels and vehicles). Limited support may also be necessary for fuel retailers wishing to provide natural gas, depending on the incentives provided by other measures.

However, it is important to recognise that developing world regions face a slightly different and more significant set of challenges if they too will follow the transitions described above. In many cases, existing infrastructure is very limited or of poor quality meaning that many of the systems described above, both physical and institutional, will need to be developed from scratch. However, this also presents potential opportunities given that today's developing economies and societies may be less dependent on current technology and fuel clusters. That is, a transition away from petroleum fuels and the ICE may be easier if this technology-fuel combination is less entrenched throughout society and the economy. However, limited resources for financing and managing the development of new infrastructure and fuel production systems in developing regions represent a significant barrier to realising a truly global sustainable transport system. Although future development may eventually circumvent this barrier, the need for early action in response to the inertia and long lead times in transforming global energy and transport systems may warrant the provision of support to developing regions in the near term. This would also be consistent with other elements of sustainable development, given the essential role of energy services in economic activity and poverty alleviation.

8.2.3 Complementary energy system developments for sustainability

As noted a number of times in this dissertation, a sustainable transport system cannot emerge in isolation of the rest of the energy system, which supplies the fuels for transport. Furthermore, it is almost certain that efforts to realise sustainable automobile transport will occur in the context of achieving broader sustainability throughout the energy system. These reasons alone necessitate the approach applied in this dissertation to the analysis of sustainable mobility; in which we developed and applied a detailed policy analysis tool covering the entire global energy system.

This approach identified a number of complementary developments in the stationary energy sector that may be necessary for mobilising more sustainable fuels for transport, and achieving a sustainable energy system. These developments were described in Chapter 7, although other elements were also discussed in Chapter 5. Three critical developments in the electricity generation sector were identified, the first of which was the additional deployment of renewable generation, such as wind turbines, solar photovoltaics and thermal technologies, and other renewables such as geothermal and limited hydroelectric power. However, given the nature of these technologies—principally their intermittency or limited scale—the deployment of natural gas generators, including single and combined cycle was an important second development that helped to significantly reduce the emissions intensity of electricity production. The final development, and perhaps the most challenging, is associated with the need to manage depletion of gas resources (and maintain security of the energy) while continuing to reduce emissions. In this analysis, nuclear power was identified as very important for achieving these multiple objectives, in Chapter 5 and Chapter 7.

However, this technology, including more advanced and theoretically inherently safe reactor designs, faces major drawbacks in terms of perceived safety, waste disposal, and possible weapons proliferation. Without trading off other elements of sustainable development encompassed in the policy analysis framework developed in this dissertation—such as accepting reduced economic growth—or technological breakthroughs, the large-scale application of nuclear power may be one of the few ways in which the enormous task of achieving long-term energy sustainability can be achieved. This will require the successful development of long-term and stable institutions, and social-political systems that can take full responsibility for nuclear waste disposal and avoid problems of proliferation.

Combining the multiple objectives of sustainable development, encompassing: ongoing economic development and satisfying increasing energy and mobility demands (particularly in today's developing world regions); climate change mitigation that ensures atmospheric CO_2 concentrations do not exceed 550ppmv; and maintenance of long-term global resources-to-production ratios for oil and gas, and long-term resource-to-consumption ratios in vulnerable world regions, is a daunting global challenge. These objectives will not be achieved without effort and commitment across the full social spectrum, requiring the lead from senior public and private decision makers. Nor, it is fair to say, will these objectives be achieved without some economic cost, despite the fact that major social benefits will accrue (and other economic costs will be avoided) as a result of realising sustainable development. This analysis, using the comprehensive ECLIPSE analytical framework, identified a total cost of approximately 2 percent of global GDP by the year 2100 (with costs only slowly increasing towards this level over the century). This can be compared with the approximate 750 percent increase in global GDP over the century included in the scenario used in this analysis. This increase is roughly equivalent to 88 percent of global GDP in 2100, indicating that the cost of achieving many elements of sustainable development may equate to less than one fortieth of the economic expansion over the 21st century. Moreover, it is also important to remember that this accounting assumes there are no economic benefits from avoiding climate change impacts, or enhancing energy security, so tends to exaggerate costs.

This completes the summary of the main broad conclusions and insights arising from this dissertation. Specific conclusions for each of the analyses in Chapter 3 to Chapter 7 were presented at the end of each chapter, and for reasons of brevity these are not repeated here.

8.3 Potential improvements and future work

The analysis in this dissertation has explored in detail a number of features of sustainable development and sustainable automobile transport. Furthermore, a comprehensive, yet flexible policy analysis tool has been developed and applied to issues associated with sustainability. However, despite the extensive methodological and analytical work presented herein, this dissertation has only touched upon many of the issues and uncertainties in long-term sustainable development, including the potential challenges arising from transport, the role of new technologies and potential policy options. Some of the additional improvements, applications and important outstanding questions are outlined below.

8.3.1 Improvements to the analytical and scenario framework

One obvious further application would be to apply the analytical framework to a range of alternative scenarios to identify more robustly important technology developments for sustainable transport in other future worlds. In particular, uncertainty over future transport demand, particularly in developing regions warrants exploration of alternative scenarios. Some preliminary work on this topic, investigating a maximum potential level of car ownership in China, is described in Turton (2006b).

An additional area for further work, and an important complement to the analysis on sustainable automobility, is to conduct a more detailed assessment of other transport modes, including high-speed railway systems and air transport, given that these represent important alternatives to the private automobile for long-distance travel. Furthermore, other transport sectors, such as freight transport and buses, may represent important niche markets in which some of the new technologies and fuels identified to be important for sustainable development may first gain a foothold. Accordingly, these other transport modes and sectors may warrant additional analysis to better understand the diffusion process for fuel cells and hydrogen. Such an analysis would require further development of the policy analysis framework to represent in a less stylised and more detailed way technologies for other transport sectors.

In addition to improving the representation of other transport sectors, a further improvement that may also help better identify potential niche markets for new technologies would be to increase the level of regional detail in the model and scenarios. This would theoretically provide a better representation of spatial sub-markets, but would require a major effort in data and scenario disaggregation.

Looking more closely at other potential improvements to the analytical framework, another area perhaps deserving further attention is the level of detail in the top-down economic model. Specifically, additional sectoral disaggregation may help elucidate more of the structural implications of achieving sustainable development, although the main insights are unlikely to change. Disaggregation to treat separately heavy industry, and apply alternative sectoral elasticities of substitution could be a demanding but interesting exercise.

8.3.2 Areas for future analysis identified by the results

Specific areas for future work were also identified from the results and insights generated in this dissertation. For instance, transmission and distribution infrastructure needs were seen to be particularly important for diffusion of alternative transport fuels. Although this was examined briefly in Chapter 4, it may be worthwhile to examine the effectiveness of alternative infrastructure policies, or assumptions.

Moreover, specific technologies were also identified to be particularly important for sustainable development, and more detailed analysis of technology support measures and their impact of sustainability may provide additional insights. Some support for the importance of technology policies such as R&D and deployment and demonstration (D&D) can be inferred from the preliminary analysis of the impact of technology support policies presented in Chapter 5 in the context of realising climate change and energy security objectives. With this in mind, some additional work exploring the role of technology R&D and D&D, in combination with climate change mitigation policies, has been conducted in Turton (2005b) and Barreto and Turton (2005;2006). Further, the framework developed in this dissertation is suitable for analysing an even broader range of policies, including different regional approaches or commitments to sustainability, and specific market-based technology policies (such as policies supporting renewables or discouraging nuclear power). In fact, this was an intended outcome of the first main theme of this dissertation to develop a flexible policy analysis tool, and the range of possible policies that can be modelled is extensive.

One particular policy area perhaps worth further exploration is security of energy supply. The analysis presented here adopts and analyses two energy security policies focussed on long-term resource availability. However, a number of alternative representations of security of energy supply policies are possible including policies aimed at a shorter time horizon or a different mix of fuels. Furthermore, policies aimed at limiting the aggregate weighted risk of the energy supply could be investigated, with each region from which imports are sourced given a different weighting based on economic and social development. In the context of energy security, alternative scenarios of global resource availability would also provide important insights, given the geological and technical uncertainty regarding future ultimately recoverable energy resources.

In addition to alternative policies for sustainable development, the modelling framework is also suitable for exploring the role of additional and more speculative technologies. Throughout this dissertation more radical technology breakthroughs were not considered due to their very high uncertainty. However, breakthroughs may substantially alter the picture presented here, and a natural next step may be to examine the potential impact of some more radical technology options. One such option mentioned in Chapter 7 is vehicle-to-grid systems, in which parked vehicles are used to provide electricity to the grid, thereby supplementing conventional generation technologies. This represents a radical change to our understanding of what a car is and does, but technologies such as these may play an important role in accelerating the shift to more sustainable transport technology options, and reducing emissions from the stationary sector. The potential of these technologies is investigated further in Turton and Moura (2006) and Moura and Turton (2006).

As a final area for future work, one critical feature that it is important not to forget when considering the results presented above in Section 8.2 (and throughout this dissertation), is the role of consumer preferences. Consumer transport purchasing decisions are not necessarily made on the sole basis of economic costs,[89] indicating the additional policy levers may be available to promote sustainable mobility (although other measures based on prices and costs may be less effective). From an analytical perspective, if one is interested in the importance of consumer behaviour, it would be interesting to apply alternative modelling approaches that do not necessarily minimise economic costs—and such an approach was applied in developing the transport demand scenarios used in this dissertation—or the represent different subgroups of consumers, such as the early-adopters, the risk-averse, and the price-insensitive submarkets.

This section has provided a snapshot of the potential applications of and improvements to the analytical framework developed as part of realising the first thematic objective of this dissertation. In addition, we have identified possible additional analyses of sustainable development and mobility that would provide insights beyond those presented in this dissertation and address some of the inherent uncertainties associated with the possible emergence of sustainable automobile transport over the long term.

[89] However, one can be more confident that vehicle manufacturers behave in a way consistent with cost-minimisation when they select engine technologies. Nonetheless, manufacturers suffer from imperfect information and are also attempting to cater to consumer markets that are not cost minimising.

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Appendices

Appendix A. Global private passenger transport

As discussed, the focus of much of this dissertation is on global automobile transport, given this sector's rapid growth. This growth is contributing to the increasing overall energy demand in road transport, which represents a major threat to longer-term sustainable development, particularly given this sector's oil dependence.

In 2000, most private passenger transport activity occurred in developed regions of the world. Table A-1 presents the number of private passenger vehicles[90] in this year for 11 world regions, estimated from a number of sources (AAMA 1996; AAMA 1997; FHA 1996; Davis and Diegel 2004; IRF 2000; EIA 1999; EIA 2002). Globally, it is estimated that there were close to 600 million passenger vehicles (cars and light trucks used as private vehicles) in 2000, although there is some uncertainty regarding these figures, particular for developing regions.[91] Thirty-five percent of these vehicles could be found in North America (NAM), around 31 percent in Western Europe (WEU) and 10 percent in the Pacific OECD (PAO) countries. Thus, almost 77 percent of all passenger vehicles are estimated to be located in these three industrialised regions.

This concentration of vehicle ownership is also reflected in estimated "motorisation rates" (i.e., vehicles per 1000 people). These are also shown in Table A-1 and appear to correlate with per capita incomes (see Figure 2-6 in Chapter 2), although other factors appear to also influence this relationship.[92] Regional vehicle ownership rates vary from 660 per 1000 people in North America (NAM) down to around 5 per 1000 people in South and Centrally Planned Asia (SAS and CPA) (based on population figures from UN 2004). For these regions it is important to note that the motorisation rate estimates exclude two-wheeled vehicles, which are a very significant transport mode in many Asian countries—for example, in India and Indonesia two-wheelers outnumber cars by up to 5:1 (and the figure may be around 3:1 in China) (IRF 2000). This is an example of what appears to be the effect of region-specific factors. The global average motorisation rate was estimated to be around 100 cars per thousand people in 2000.

One key question for exploring the possible emergence of a future sustainable transport system is whether economic development in today's developing countries will lead to demands for the same levels of personal mobility that exist in today's industrialised regions. The figures in Table A-1 provide some guidance for answering this question in terms of possible scope of future levels of global car ownership, which in turn has implications for

[90] Private passenger transport can normally be thought of as car transport. However, in North America a majority of the light vehicles sold today are light-duty trucks instead of cars (with light trucks accounting for 52.8 percent of light vehicle sales in 2003, according to Davis and Diegel (2004, Table 4.9)). Since most of these are used for personal transport (75 percent in 1997, based on Davis and Diegel (2004, Table 5.7)), it is more accurate to use the broader term "private passenger vehicle". For convenience, however, we will use this term and the term "car" interchangeably to cover private passenger vehicles.

[91] And probably around 800 million of all types of road vehicles with 4 wheels or more (based on the same sources). In developing regions, commercial vehicles represent a much larger share of total vehicle fleet than in developed regions (AAMA 1997; IRF 2000).

[92] For example, region-specific factors are apparent for North America, where vehicle ownership rates are more than 50 percent above those in other industrialised regions, and in sub-Saharan Africa, which has higher vehicle ownership rate than the relatively richer South Asian and CPA regions, although lower numbers of two-wheelers. We can speculate that the latter may be because of lower population densities in sub-Saharan Africa along with less-developed alternative transport modes.

energy demand and greenhouse gas emissions. The role of transport on these and other elements of sustainable development is explored throughout this dissertation.

Table A-1 Estimated number of passenger vehicles (cars and light trucks used as cars) in millions, and number per 1000 persons in 2000

World Region	**Passenger vehicle numbers** (millions)	**Motorisation rates** (PMV/1000 people)
North America (NAM)	211.1	660
Western Europe (WEU)	188.3	410
Pacific OECD (PAO)	60.5	403
Former Soviet Union (FSU)	18.1	62
Eastern Europe (EEU)	18.0	148
Centrally-Planned Asia (CPA)	6.9	4.9[a]
South Asia (SAS)	7.4	5.4[a]
Other Pacific Asia (PAS)	26.3	55[a]
Latin America (LAM)	41.8	81
Middle East and North Africa (MEA)	11.8	34
Sub-Saharan Africa (AFR)	9.5	15
World	599.7	(avg.) 99

a. Note, in these regions two-wheelers represent a very substantial part of the private vehicle fleet. For example, in China, India and Indonesia, it is estimated that there are 3-5 times as many motorised two-wheelers as there are cars. Accordingly, the level of private mobility is under-estimated if one considers car numbers alone.

Source: Estimates based on AAMA 1996; AAMA 1997; FHA 1996; Davis and Diegel 2004; IRF 2000; EIA 1999; UN 2004.

Appendix B. Passenger car technologies, costs and efficiencies

B1. Transport technology characteristics and prospects

As discussed in Chapter 2, future population growth and increasing incomes throughout the world are expected to drive increasing demands for private mobility, particularly automobile transport. Satisfying this future global demand is likely to pose many challenges to long-term sustainable development. In particular, the need to reduce greenhouse gas emissions to avoid the worst impacts of climate change, and to manage non-renewable energy resources are two challenges that appear incompatible with a large expansion in automobile use.

However, as briefly discussed in Chapter 2 and Chapter 3 (and later chapters), the application of new technologies has the potential to alleviate some of these impacts. For instance, vehicle technologies able to achieve high fuel efficiencies, or utilise alternative renewable energy sources represent promising possibilities for satisfying mobility demands while avoiding some of the negative impacts of transport on sustainability. The potential far-reaching impact of technology is perhaps best appreciated by considering the role of the internal combustion engine (ICE) in the 20th century. This technology transformed personal mobility in the developed world and in doing so strongly influenced the development of human settlements, trade, tourism and communication. Moreover, the ICE also transformed global energy production, and has indirectly influenced historical and current global geopolitics. One key question is whether this technology will maintain its place in the 21st century, or be replaced by an alternative.

With this in mind, this appendix outlines some of the technology options for transport and their prospects. This is mainly for readers unfamiliar with the various alternative vehicle technology options such as hybrid-electric and fuel cell technologies, and alternative fuels. Importantly, this appendix discusses current characteristics and performance of different technologies, and it should be remembered that our interest is on long-term technology prospects and sustainable development. Parts of Appendix Sections B1 and B2 are based on Miketa and Schrattenholzer (2004) and Ryan and Turton (2006).

Consistent with the second theme of this dissertation, the primary focus here is on technologies that are applicable to private passenger transport, although many described below can be used in other transport applications, particularly road, rail, water and some types of air transport.[93] Furthermore, the emphasis here is on those engine technologies that are technically proven, although they may still face a number of challenges to achieve commercial viability, and hence not every possible innovation in engine technology is considered (such as large fly wheels, or compressed air).

B1.1 Internal combustion engine (ICE) vehicles

The ICE is a mature technology that has undergone a massive amount of technological development, and continues to receive enormous R&D support, which is likely to sustain its dominance of the automobile and truck market for at least the medium term. Almost all of today's road vehicles are powered by internal combustion engines (ICEs), in which combustion is induced by a spark or by compression. At present, the spark ignition engine (usually gasoline-fueled) is cheaper, smaller, lighter and quieter than the diesel compression

[93] A large amount of air transport relies on the jet engine, which the technologies discussed in this section are unlikely to replace without major unexpected technological breakthroughs.

engine and offers reasonable performance, although with relatively lower fuel efficiency. Potential efficiency improvements are discussed in Appendix B2.

ICE vehicles using non-petroleum fuel configurations are also available. For example, around half a million compressed natural gas (CNG) vehicles are estimated to be in use in OECD countries (IEA 1997).[94] However, this technology currently faces challenges related to fuel storage, with the low energy density of natural gas potentially limiting vehicle range. Alcohol fuels, typically methanol and ethanol, are also proven alternatives to petroleum fuels for ICE vehicles. Brazil, the USA, Sweden, and Canada are among the countries that have commercially introduced ethanol and methanol, both in gasoline blends and neat (AFDC 2003; IEA 1997). Non-alcohol biofuels, such as biodiesel also represent a potentially important alternative fuel. However, large-scale production of biodiesel is likely to rely principally on oil crops, which are generally lower yielding than the cellulosic and starch crops that can be used for alcohol production. This lower yield is likely to favour alcohol-based biofuels.

These represent some of the existing, and in some cases widespread, alternative fueling options. Other fueling options are also available, including the use of hydrogen in ICE vehicles.

B1.2 Electric vehicles

Unlike ICE vehicles which use a series of controlled explosions to generate the motive power required for travel, electric vehicles employ a completely different engine system that instead relies on an electric motor. Electric vehicles can achieve very high levels of efficiency compared to ICE vehicles, and the electricity used to power the vehicles can be obtained from a range of fuels, reducing dependence on petroleum products, and potentially enabling vehicles to be powered by renewable energy sources like solar, wind or hydroelectric power. However, the critical issue for electric vehicles is how to store and supply the electric power for the electric motor, and this is discussed below.

B1.2.1 Battery electric vehicles

As the name suggests, battery electric vehicles store the electricity used to power the vehicle in on-board batteries, and these batteries are recharged by connecting the vehicle to the electric grid (AFDC 2003). The potential impact of battery electric vehicles on long-term sustainability is therefore highly dependent on the fuels and technologies used for electricity production. However, the cost and performance of battery EVs is ultimately determined by the cost and performance of the energy storage batteries. Currently several types of automotive batteries are available and/or under development, although even the best of these has an energy density well below that of gasoline. This is partly offset by the greater efficiency of electric motors, but the driving range of EVs is still very limited and without major technological breakthroughs, electric vehicles are considered unlikely to be accepted by consumers as a practical alternative to ICE vehicles (DOE and EPA 2003a; Chalk and Miller 2006).

[94] It should also be mentioned that liquefied petroleum gas (LPG), a by-product of crude-oil refining consisting mainly of butane and propane, is also used in limited quantities. In the longer term it may offer some advantages over natural gas as a result of its higher energy density and ease of transportation (IEA 1997).

B1.2.2 Fuel cell vehicles

One way to overcome the problems associated with batteries in electric vehicles is to instead generate electricity on-board using another energy carrier. The main problem with this approach is that it may completely undermine the efficiency benefits of using an electric motor, unless an extremely efficient electricity generation technology is available. Fuel cells represent such a technology.

Fuel cell vehicles (FCVs) represent a radical departure from vehicles with conventional internal combustion engines. Like electric vehicles with batteries, FCVs are propelled by electric motors, and are also able to achieve high system efficiencies. However, unlike battery vehicles, FCVs generate their own electric power on board through an electrochemical process using hydrogen fuel (pure hydrogen or hydrogen-rich fuel such as methanol, natural gas, or even gasoline) and oxygen from the air. The fuel cell separates the protons and electrons in the hydrogen fuel—the protons then travel through the electrolyte, whilst the electrons must travel through an electric circuit, thereby generating power (EERE 2005). Importantly, fuel cells must overcome a number of technical challenges before they can be widely adopted for transportation, including the need to increase durability and dependability.[95]

There are a number of ways of supplying hydrogen to the PEM fuel cell, and these are examined below.

i) Hydrogen fuel cell vehicles

Hydrogen can be supplied to the fuel cell directly with pure hydrogen stored in the vehicle. FCVs fueled with pure hydrogen emit no pollutants, only water and heat. In addition, the possibility of producing hydrogen from a variety of primary-energy sources makes it an extremely attractive fuel.

However, the biggest challenge confronting FCVs fueled directly with hydrogen is fuel storage. Hydrogen can be stored onboard in a number of ways, but among those receiving the most attention is storage in high-pressure tanks. This storage option still faces a number technical challenges, given that hydrogen has a high energy density per unit weight but a low energy density per unit volume, so it is difficult to store the volume of hydrogen needed to generate the same amount of energy stored in a small volume of conventional fuels such as gasoline. This is a significant problem for fuel cell vehicles (and hydrogen ICE vehicles), which need to achieve a driving range of 500-600 kilometres between refueling in order to be attractive to customers and competitive with gasoline vehicles. Research is also being conducted into the use of other storage technologies such as metal hydrides, carbon nanostructures (materials that can absorb and retain high concentrations of hydrogen) and liquid hydrogen (EERE 2005; Doyle 1998).

Besides these technical difficulties of storing hydrogen on board of a vehicle, the distribution of hydrogen may be the other major barrier to its widespread use. The cost of cryogenic or pipeline transport to retail fueling stations, as well as of storage (infrastructure, refrigeration costs), could be relatively high (IEA 1997). To circumvent these difficulties, alternatives such as using a fuel that is a more conveniently handled and from which hydrogen can be produced on board the vehicle, are being tested and show technical potential (see the section, below).

[95] For example, PEM fuel cells require effective water management systems to operate dependably and efficiently.

ii) Alcohol or petroleum FCV with on-board reforming

Fuel cell vehicles can also be fueled with hydrogen-rich fuels, such as methanol, ethanol, natural gas, or even petroleum fuels. However, these fuels must first be reformed on board the vehicle to produce pure hydrogen for the fuel cell. Because all these fuels contain carbon, the reforming process results in some emissions of CO_2, but the much higher efficiency of the fuel cell means that the level of emissions is much lower than for a comparable gasoline vehicle (DOE and EPA 2003b). Moreover, reforming these fuels results in much lower levels of all other air pollutants compared to direct combustion.

There are two main advantages of fuel cell vehicles with an onboard reformer compared to FCVs using pure hydrogen. Firstly, reformers allow the use of fuels with higher energy density than that of pure hydrogen gas. Second, and more importantly, reformers allow FCVs to use conventional fuels delivered using the existing infrastructure, avoiding the need to develop new and costly infrastructure before FCVs can be adopted on a large scale. Although the fuel efficiency of a fuel cell vehicle with hydrogen produced from an on-board reformer is less than a fuel cell vehicle using hydrogen as stored fuel, they are still able to achieve high fuel economies.[96]

The main disadvantage facing this type of FCV is that onboard reformers add to the complexity, cost, weight and maintenance demands of the vehicle (EERE 2005).

B1.3 Hybrid ICE-electric vehicles

The technologies and fuels discussed so far have been delineated into two main groups—ICE- and electricity-based vehicles. However, it is also possible to combine, or hybridise, mechanical and electrical conversion technologies on board a single vehicle to exploit the advantages of each. In the most general sense, hybrid vehicles combine two or more energy conversion technologies (e.g., internal combustion engines, fuel cells, generators, or motors) with one or more energy storage technology (e.g., fuel, batteries, ultracapacitors, or flywheels). Within this broad classification, one commercial example is hybrid ICE-electric vehicles, which combine elements of battery electric and ICE vehicles, and represent a transition from an existing technology as opposed to a radical departure like FCVs. Hybrid-electric vehicles (HEVs) are generally fueled in the same way as ICEs—that is, all the fuel alternatives discussed in relation to ICEs in Section B1.1 apply to HEVs.

Currently, there is no single definition of a hybrid vehicle, and a number of manufacturers are experimenting with different combinations of technology components. HEV systems can be defined in terms of four main elements. The first is “stop and go” ICE technology, whereby the ICE is switched off when the vehicle is stationary, instead of idling, and an electric motor is used to restart the vehicle (similar to the starter motor in conventional ICEs). This has the potential to reduce engine wear, fuel consumption and pollutant emissions. The second feature is regenerative braking, where some of the kinetic energy from the vehicle’s motion is captured and stored (in a battery or super-capacitor) during braking, instead of being dissipated in the form of heat on the brake-pads. This improves fuel efficiency because the ICE is not used to charge the battery and, when combined with the two features discussed below, the electric energy can also be used to propel the vehicle. The third and perhaps most important feature of hybrid vehicles is electric-motor assist of the ICE, where the electric

[96] In the range 2.9-3.9 litres per 100 kilometres (60-80 mpg), compared to 2.8-3.4 l $100km^{-1}$ (70-85 mpg) for hydrogen FCVs (Marx 2000).

motor powers the driveshaft. This enables increased power output with a smaller ICE, and avoids the need to operate the ICE outside its optimal power output range. The smaller ICE reduces fuel consumption, and operating the engine in its optimal range greatly improves tailpipe emissions. The fourth element, and the logical extension of electric motor assist, is fully independent electric drive powered either by the battery alone, or through an alternator powered by the ICE. This enables the vehicle to operate in electric-drive mode, usually at low speeds.

Hybrids may include some or all of these futures—the more features that are included the better the energy efficiency (and "stronger" the hybridisation), but the more complex and costly the system. Generally the larger the role played by the electric motor, the larger battery system required. Of the hybrid vehicles already on the market, the Honda Insight, Accord and Civic hybrids have relatively small electric motors (10-12 kW), and are 'mild hybrids' whereas the Toyota Prius (50 kW), Lexus RX400h and Ford Escape (70 kW) are able to operate in fully electric mode, and electric motor assist contributes more to total power output (CARB 2005).

Some manufacturers are also experimenting with alternative engine cycles—for example, the Ford Escape[97] and Toyota Prius use the Atkinson cycle (as opposed to the Otto cycle used in most ICE vehicles) which sacrifices power for even greater efficiency by employing different expansion and compression ratios in the engine stroke. The power sacrifice can be compensated by the electric motor in the HEV.

Fuel cell vehicles can also be hybridised to incorporate regenerative braking and battery assist to the fuel cell. Similar to the ICE-electric hybrids, this means a smaller fuel cell is required, since the battery system is able to supplement the output of the fuel cell during times when peak power output is required—for instance during acceleration. Because fuel cell systems themselves are currently very costly, this has the potential to significantly reduce the cost of fuel cell vehicles.

B2. Car transport technology efficiencies and potential improvements

Estimates of vehicle technology drive-train fuel efficiency were derived from Weiss *et al.* (2003), Thomas *et al.* (2000), Weiss *et al.* (2000), ADL (2002) and Ogden *et al.* (2004), and are reported in the main text of this dissertation in Section 3.3.3.4. Regional vehicle fuel efficiencies for developed regions were obtained from Landwehr and Marie-Lilliu (2002). Fuel efficiency in developing regions, where data are unreliable or unavailable, was assumed to be roughly the average of that in the developed regions. This is probably unrealistic in the base year because in many of these regions there is a lack of adequate vehicle maintenance and poor quality roads (Michaelis 1996). However, private passenger vehicle travel consumes a relatively small amount of energy in the base year in these regions, and any significant increase in vehicle numbers is likely to coincide with an improvement in overall vehicle fuel efficiency, and convergence with developed regions (because of demand for improved roads, increased availability and competition in vehicle maintenance industry and more competition with foreign vehicle manufacturers). Accordingly, the estimates used for projecting developing region fuel economy are likely to be reasonable over the longer term, when this form of travel becomes more significant.

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[97] See http://www.fordvehicles.com/suvs/escapehybrid/features/specs/

A number of sources in the literature (discussed below, but based on the review in Miketa and Schrattenholzer (2004) and Ryan and Turton (2006)) were used to estimate the potential for vehicle efficiency to improve over time, particularly those improvements unrelated to drivetrain technology. However, much of this literature focuses on the short to medium term, whereas our interest is the long term. Accordingly, the focus below is on the more technologically optimistic or aggressive assessments of potential efficiency improvements over the short-term, which may provide a good indication of long-term potential under more modest assumptions.

Turning to specific studies, the National Academy of Science's (NAS 2002) most aggressive technology path for the next 10-15 years, including the introduction of emerging technologies, is estimated to achieve reductions in fuel consumption ranging from 27.9 to 36.7 percent for different car types.[98] This is consistent with the results of the Massachusetts Institute of Technology's (Weiss *et al*. 2000) simulation of future fuel consumption rates for gasoline/diesel cars, which estimates that under an advanced technology case fuel consumption rates could decline between 45 and 50 percent by 2020. This estimate accounts for the impact of advanced body designs, lightweight materials and improvements to the ICE. Assuming a slightly less aggressive technology path, such improvements are likely to occur instead over a longer timeframe. For example, the US National Research Council (NRC 1992) made a more modest projection of the potential impact of the uptake of specific, well-established and proven technologies that could be implemented by car makers as part of the normal replacement cycle for manufacturing equipment in 15 years or less. They estimated improvements for cars and light trucks ranging from 22 to 26 percent.

The US Office of Technology Assessment (OTA 1995) has also assessed the possible fuel efficiency performance of advanced vehicles to be introduced during the next 10 to 20 years. Based on a survey of car manufacturers, the maximum fuel consumption improvement that could be achieved by an advanced ICE vehicle was estimated at 56 percent compared to the current *average* new car, while maintaining interior space and performance constant at 1995 levels. To achieve this fuel economy, vehicles would need to combine an optimised aluminium body, continuously variable transmission, advanced low rolling resistance tyres and advanced ICE technology. The IEA (1997) roughly estimates that ICE efficiency could be improved by a maximum of 20 percent with improved exhaust treatment, improved combustion, and fast warm-up.

Clearly, the consensus among these and other sources (such as Schafer *et al.* 1999; Lightfoot and Green 2001) is that there is considerable technological potential to improve the efficiency of the automobile. It would probably not be unreasonable to assume that average fuel consumption rates could be reduced by 50 percent over the 21st century, excluding the impact of hybrid systems or fuel cells. Moreover, many of these technology developments will benefit all passenger vehicles regardless of engine technology, including improvements resulting from the application of lightweight materials, reduced rolling resistance tyres and better aerodynamics. On the other hand, improvements to engine features, such as variable value timing and direct fuel injection are specific to ICEs. Considering that fuel cells are relatively less mature, significant efficiency improvements can also be expected for this technology.

However, one must be cautious when considering the overall impact of these efficiency technologies on the vehicle fleet. In particular, the impact of other likely developments in the

[98] The analysis was done separately for 10 weight classes, including cars, SUVs, mini-vans, and pickup trucks.

vehicle market should also be considered. This is illustrated by a US Energy Information Administration (EIA 2003) study which examined not only the impact of technologies, but also that of structural changes in the automobile market. They forecast for the USA that advanced technologies such as variable valve timing and direct fuel injection, as well as electric hybrids for both gasoline and diesel engines would decrease average fuel consumption of new light duty vehicles by only 8 percent by 2025. Importantly, under this case it was assumed that fuel efficiency standards remained at current levels, fuel prices stayed low and *higher personal income increased the demand for larger and more powerful cars* (emphasis added).[99]

This analysis by the EIA (2003) captures the impact of current trends in the USA, where a shift from cars to light trucks is largely responsible for average private passenger vehicle fuel efficiency having increased by only 8 percent between 1980 and 2003,[100] even though tighter standards led improvements in car fuel efficiency of roughly 21 percent over the same period (Davis and Diegel 2004, Table 4.18). Moreover, such trends towards larger vehicles are not confined to the USA, with average new-car weight in the European Union increasing by 25 percent between 1980 and 1999, and average new vehicle power increasing by 40 percent (ECMT 2003).[101]

The fact that without policies supporting improved efficiency standards, the impact of structural changes—such as a shift to larger vehicles—on the automobile market could substantially offset what would otherwise be large improvements in fuel economy, illustrates two important features for further analysis. First, it highlights the importance of increasing incomes and consumer vehicle preference, and second, it illustrates a potential need for policy to support deployment of even more efficient new technologies in order to improve fleet fuel economy. These issues are explored in more detail in Chapters 4 and 7.

On the basis of the above studies, the efficiency of the conventional internal combustion engine vehicle is assumed to improve at 2 percent per decade.[102] This conservative estimate is used to reflect that improvements in vehicle weight, aerodynamics, rolling resistance etc., will be offset somewhat by demand for larger vehicles with more energy-consuming onboard systems as incomes grow. The relative efficiencies of alternative drivetrains (presented in Figure 3-11 in Section 3.3.3.4) are assumed to remain constant—that is, all technologies are assumed to benefit equally from efficiency improvements unrelated to vehicle drivetrains.

B3. Car technology component costs and learning

Three components used in the ten engine-fuel technology combinations studied in this dissertation are assumed to benefit from learning-by-doing. These comprise: the fuel cell (FC); the fuel processor (reformer) used with the alcohol and petroleum fuel cell; and the hybrid battery system. Non-learning components comprise the internal combustion engine, fuel storage systems, electric motor, generator, transmission and control systems. The relationship between technologies and learning components is presented in Table 3-4 in the main text.

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[99] It is also worth restating that this estimate includes the impact of the introduction of hybrid-electric vehicles.
[100] The market share of light trucks increased from 19.6 to 52.8 percent over the same period (Davis and Diegel 2004, Table 4.9).
[101] Based on eight EU countries from 1980-1994 and 13 countries from 1995-1999.
[102] Noting that this excludes the potential impact of hybrid or fuel cell technologies.

Total drive train system costs for mass-produced vehicles were derived from Ogden *et al.* (2004); Weiss *et al.* (2000), Thomas *et al.* (2000) and ADL (2002) (although the estimates in latter were somewhat higher). The derivation of the costs of the various learning components—FC, reformer and hybrid battery system—used in the car transportation technologies is discussed below. Vehicle drivetrain cost estimates, with and without the assumed impact of learning, are presented in Table B-1.

The electric hybrid system (comprising electric motor, generator and battery system) used in both the ICE-electric hybrids and the FC-battery hybrids is assumed to cost $1600 per mass-produced vehicle, based on estimates of battery cost of around $700 and motor, generator and control system costs of $900, consistent with a number of estimates (Ogden *et al.* 2004; Weiss *et al.* 2000). However, current battery costs are 2.5-4 times estimated potential (ADL 2002). This guides the starting and floor costs for the battery system used in HEVs and FCVs.

Complete fuel cell system costs for 2001 are estimated to be US$324/kW (Carlson *et al.* 2002) for a 50 kW PEM system. The majority of this (US$220/kW) is for the fuel cell subsystem and reformer (US$76/kW). However, these costs are expected to decline, and various sources present estimates of likely future FC prices of US$30-60/kW, with a full direct hydrogen fuel cell system cost ranging from US$50 to $110/kW (with reformer-based petroleum and alcohol systems likely to cost an additional US$20-50/kW) (ADL 2002; Carlson *et al. 2*002; Ogden *et al. 2*004; Weiss *et al. 2*000).

A power output of 40 kW per PMV is assumed in this dissertation, roughly in line with estimates for a battery-hybrid FC vehicle (ADL 2002; Ogden *et al.* 2004; Ogden *et al.* 2000). At this output slightly higher starting costs for the FC subsystem and reformer unit have been assumed ($250/kW and $90/kW, respectively) in line with Carlson *et al.* (2002). A mid-point in the range of future FC prices is used as the floor costs for this technology.

Methanol-based steam reformers (SR) are expected to remain cheaper than the auto-thermal reformers (ATR) required for gasoline fueled FCVs (ADL 2002; Thomas *et al.* 2000), and both fuel processing systems will require a more costly FC to cope with the lower fuel quality. Future reformer costs range from $10-20/kW for steam, and $20-40/kW for auto-thermal (Ogden *et al.* 2004), which is consistent with Thomas *et al.* (2000) and Weiss *et al.* (2000). For this analysis, we have taken a floor cost of $25/kW for the SR and a starting cost of $90/kW (the latter based on Carlson *et al.* 2002).[103]

Table B-2 shows the starting and floor costs, along with the assumed learning rate for each component. Higher learning rates have been assumed for the less mature components (FC and B). The rates presented in Table B-2 are the initial rates defined according to the entire component cost (noting that the inclusion of floor costs changes the effective rate) and are within the ranges suggested by others (for example, see McDonald and Schrattenholzer 2001; Tsuchiya and Kobayashi 2002).

[103] Starting and floor costs for auto-thermal reformers have been assumed to be $110/kW and $45/kW, respectively.

Table B-1 Estimates of car technology and component costs (US$2000)

Components		Internal combustion conventional (petroleum) ICC	Internal combustion natural gas (gas) ICG	Internal combustion alcohol (alcohol) ICA	Internal combustion-electric hybrid (petroleum) ICH	Internal combustion (gas)-electric hybrid (gas) IGH	Internal combustion (alcohol)-electric hybrid (alcohol) IAH	Internal combustion (H_2)-electric hybrid (H_2) IHH	Direct H_2 FC-battery hybrid (H_2) HFC	Petroleum ATR-FC-battery hybrid (petroleum) PFC	Methanol-SR-FC-battery hybrid (alcohol) AFC
		Transport technologies									
Learning components (floor cost)	Basic FC								1,800	1,800	1,800
	Basic fuel processor (reformer)									1,000	1,000
	Battery system				700	700	700	700	700	700	700
Non-learning components	ICE	1,600	1,600	1,600	900	1,000	900	900			
	Storage tank	100	500	100	100	300	100	1,400	1,100	100	150
	Motor, generator and control				900	900	900	900	900	900	900
	Transmission	700	700	700	700	700	700	700	200	200	200
	FC premium									1,000	650
	Processor premium									800	
Total cost (floor cost)		**2,400**	**2,800**	**2,400**	**3,300**	**3,600**	**3,300**	**4,600**	**4,700**	**6,500**	**5,400**
Incremental cost relative to ICC		*0*	*400*	*0*	*900*	*1,200*	*900*	*2,200*	*2,300*	*4,100*	*3,000*
Incremental cost relative to ICC of non-learning components			*400*	*0*	*200*	*500*	*200*	*1,500*	*-200*	*600*	*-500*
Learning components (initial costs)	Basic FC								10,000	10,000	10,000
	Basic fuel processor (reformer)									3,600	3,600
	Battery system				2,500	2,500	2,500	2,500	2,500	2,500	2,500
Initial cost premium over ICC			*400*	*0*	*2,700*	*3,000*	*2,700*	*4,000*	*12,300*	*16,700*	*15,600*

Table B-2 Starting costs, learning rates and floor costs for car transport technologies

Component	Starting cost ($/kW for 40 kW FC)	Learning rate	Floor cost ($/kW for 40 kW FC)
Fuel cell (FC)	250 (266 AFC) (275 PFC)	15%	45 (62 AFC) (70 PFC)
Reformer (R)	90 (110 PFC)	5%	25 (45 PFC)
Hybrid battery system (B)	$2,500 per vehicle	15%	$700 per vehicle

Note: Currency units are 2000 US dollars.

Appendix C. Stationary energy technology components and costs

C1. Electricity generation and energy carrier components

The initial costs of the various new components incorporated into the ERIS model and used in stationary electricity generation are discussed below. Some of these components, such as the gasifier and reformer, are also used in some of the energy carrier production technologies.

The stationary fuel cell (FC) system is assumed to comprise two learning components: one that is specific to stationary FC applications and another that is common to both stationary and mobile fuel cells. As a consequence, installation of a stationary FC results in some spillover benefits to mobile applications and vice versa, although there is a limit to the amount which total system costs can decline as a result of the installations of the common component. The stationary-specific FC component is assumed to cost US$1250/kW, while the common component costs US$250/kW (corresponding to the cost of the mobile FC discussed in Appendix B).[104] This approach captures learning spillovers between the stationary and mobile fuel cell technologies.

Gas turbines are assumed to cost US$200/kW (Parsons and Shelton 2002), representing roughly 2/3[rds] of the cost of a gas turbine generation plant. This component is used in advanced coal (IGCC), gas turbine and gas combined cycle generation.

Gasifiers, comprising air separation, oxygen compressor and gasification, are assumed to cost US$250/$kW_{th}$, which is equivalent to US$400-500/$kW_e$ for an IGCC plant (Parsons and Shelton 2002; Hamelinck and Faaij 2001). This component is used in advanced coal generation (IGCC), coal-to-liquids (Fischer-Tropsch) synthesis, production of hydrogen from coal and biomass and production of alcohols from biomass.

The steam reformer (combined with a Pressure Swing Absorber (PSA)) is estimated to cost US$180/kW (Simbeck and Chang 2002; Hamelinck and Faaij 2001), and we have assumed the same relative learning potential as for transport-based steam reformers. In stationary applications, this component is used in the gas fuel cell, and in hydrogen and alcohol production from natural gas.

C2. Carbon capture technologies

Overall costs of carbon capture technologies are based on David and Herzog (2001). The costs of the components (learning and non-learning) that make up these technologies have been sourced from Kreutz *et al.* (2003) and Parsons and Shelton (2002) and are discussed below.

CO_2 stripping, based on the SELEXOL process, is reported to cost US$140/$kW_e$ for an IGCC plant (Parsons and Shelton 2002) after grossing up process costs to total plant investment. Using Parsons and Shelton's (2002) emissions factors, this translates to around US$70 for a carbon (C) processing capacity of one ton per year. Kreutz *et al.* (2003) suggest a lower price

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104 To illustrate, each dollar spent on a stationary FC system has the same impact on learning-by-doing in the mobile FC of a direct investment of around 17 cents. Conversely, each dollar invested in mobile FC capacity affects learning in one-sixth of the total installation cost of a stationary FC.

for SELEXOL adsorption. However, they have assumed lower balance of plant, engineering, contingency and miscellaneous cost.[105]

Parsons and Shelton (2002) estimate the capital costs of the amine process for CO_2 separation from lower concentration flue gas streams. They estimate CO_2 separation costs of US$165/tC/yr for conventional coal generation and US$325/tC/yr for gas generation. Combined with CO_2 compression and drying costs of around US$40-50/tC/yr (Parsons and Shelton 2002; Kreutz *et al. 2*003), these figures are comparable to those of David and Herzog (2001).

Carbon transport and storage costs are estimated to be US$26/tC, based on estimates of Freund *et al.* (2003). They report that a plausible range for costs of storage of CO_2 in deep saline aquifers or depleted oil/gas fields is US$1-3/t$CO_2$ (US$3.7-11/tC). Here we have adopted the mean value of this range, which corresponds to US$7.3/t C, for our calculations. It must be recognised, however, that many uncertainties surround these figures. Also, the storage costs will depend on the particular characteristics of specific reservoirs, the rates of injection etc.

As for transportation of captured CO_2 from the sources to the reservoirs, again Freund *et al.* (2002) mention a likely range of US$1-3/t$CO_2$/100 km (US$3.7-11/tC/100 km). Using the mean value and a pipeline length of 250 km, we arrive at US$5/t CO_2/250 km (or US$18.3/tC/250 km), the figure used here.

[105] Kreutz *et al.* (2003) present the costs of the hydrogen sulfide (H_2S) absorption, conversion and purification system differently to other authors (for example, Parsons and Shelton 2002) who include the costs of H_2S removal (excluding the Claus and SCOT units) in the cost of the SELEXOL unit. Adding H_2S removal costs, minus the costs of the Claus and SCOT units, raises the cost of the SELEXOL system to a similar level as in Parsons and Shelton (2002).

Appendix D. Learning curves for selected technology components in ERIS

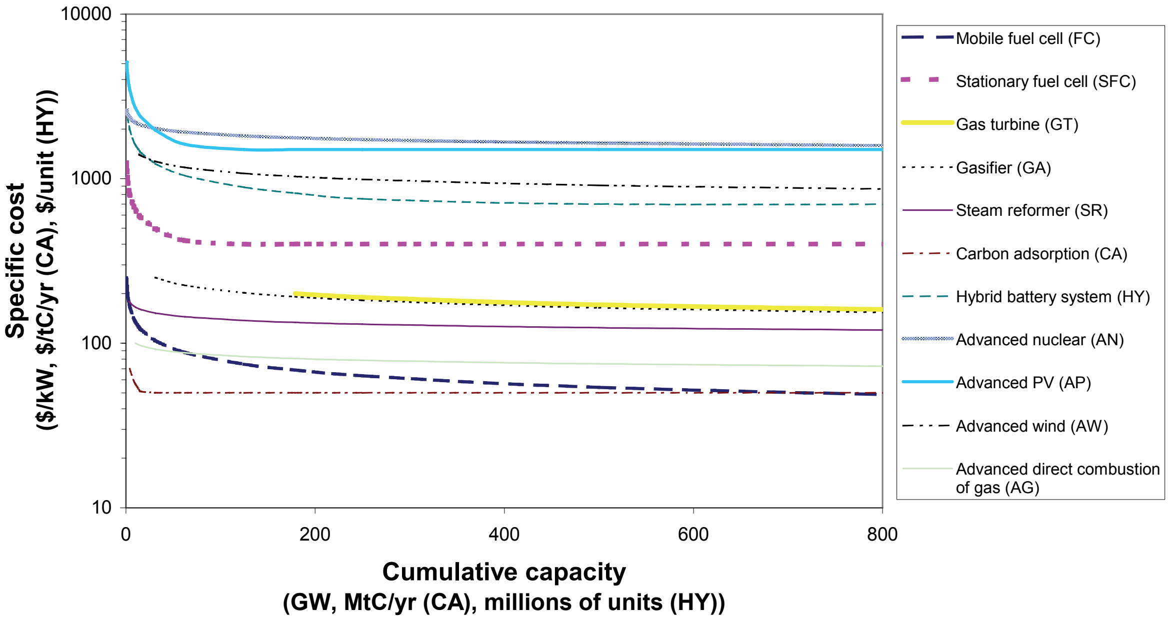

Figure D-1 One-factor learning curves for selected technology components in the ERIS model

Note: specific costs are given in US$ dollars per kW, with the exception of the carbon adsorption system (US$/t /yr) and the hybrid battery system (US$/unit).

Acronyms and abbreviations

1FLC	one-factor learning curve
AFC	alcohol SR-fuel cell electric hybrid
AFR	sub-Saharan Africa
ATR	auto-thermal reformer
avg.	average
C	carbon
C-e	carbon-equivalent
CCS	carbon capture and storage
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CPA	centrally planned Asia
CTL	coal-to-liquids
D&D	demonstration and deployment
E3	energy-economy-environment
EC	European Commission
ECLIPSE	Energy and Climate Policy and Scenario Evaluation
ECS	Environmentally Compatible Energy Strategies (IIASA)
EDGAR	Emission Database for Global Atmospheric Research
EEU	Central and Eastern Europe
EIT	economies in transition
EPPA	Emissions Prediction and Policy Analysis
Eq./Eqs.	equation(s)
ERIS	Energy Research and Investment Strategies
ETH	Swiss Federal Institute of Technology
FC	fuel cell
FCV	fuel cell vehicle
FSU	newly independent states of the Former Soviet Union
FT	Fischer-Tropsch
g	gram(s)
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GHG	greenhouse gas
H_2	hydrogen (molecular)
H_2S	hydrogen sulfide
HEV	hybrid electric vehicle
HFC	direct H_2 fuel cell electric hybrid
IAH	internal combustion (alcohol) electric hybrid
ICA	internal combustion alcohol
ICC	internal combustion conventional (petroleum)
ICG	internal combustion natural gas
ICH	internal combustion (petroleum) electric hybrid
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IGH	internal combustion (gas) electric hybrid
IHH	internal combustion (H_2) electric hybrid
IIASA	International Institute for Applied Systems Analysis
IPAT	Impact = Population x Affluence x Technology
IPCC	Intergovernmental Panel on Climate Change
I-O	input-output
J	joule(s)
km	kilometre(s)
l	litre(s)
LAM	Latin America and the Caribbean
LP	linear program(ming)

LPG	liquid petroleum gas
LR	learning rate
MAC	marginal abatement cost
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MARKAL	Market Allocation
MEA	Middle East and North Africa
MERGE	Model for Evaluating Regional and Global Effects of GHG reductions
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MINIMA-SUD	Methodologies for Integrating Impact Assessment in the Field of Sustainable Development
MIP	mixed integer program(ming)
MPC	marginal product of capital
mpg	miles per gallon
N_2O	nitrous oxide
NAM	North America
NO_x	oxides of nitrogen
OECD	Organisation for Economic Co-operation and Development
pa	per annum
PAO	Pacific OECD
PAS	other Pacific Asia
PEM	polymer electrolyte/proton exchange membrane
PFC	petroleum ATR-fuel cell electric hybrid
pkm	passenger-kilometre
PMV	private motor vehicle
ppmv	parts per million volume
PPP	purchasing power parity
PSA	pressure swing absorber
PSI	Paul Scherrer Institute, Switzerland
PV	photo-voltaic
R&D	research and development
RD3	R&D, demonstration and deployment
REEI	reference energy efficiency improvements
RES	reference energy system
RHS	right-hand side
ROW	rest of the world
Rsc:C	resource-to-consumption ratio
Rsc:P	resource-to-production ratio
R:P	reserves-to-production ratio
SAPIENT	Systems Analysis for Progress and Innovation in Energy Technologies
SAPIENTIA	Systems Analysis for Progress and Innovation in Energy Technologies for Integrated Assessment
SAS	South Asia
SCOT	Shell Claus Off-gas Treatment
SELEXOL	carbon dioxide physical adsorption process
SF_6	sulfur hexafluoride
SO_2	sulfur dioxide
SO_4^{2-}	sulfate anion
SR	steam reformer
SRES	Special Report on Emissions Scenarios (IPCC)
t	tonne(s)
TAR	Third Assessment Report (IPCC)
TEEM	Energy Technology Dynamics and Advanced Energy System Modeling
TTW	tank-to-wheels
TU Wien	Vienna University of Technology
T&D	transmission and distribution
UDF	utility discount factor
UK	United Kingdom of Great Britain and Northern Ireland
UN	United Nations
US, USA	United States of America
VOCs	volatile organic compounds

W	watt
Wh	watt-hour
Wy	watt-year
WEU	Western Europe and Turkey
WTT	well-to-tank
WTW	well-to-wheels

The following suffix abbreviations are used with g, J, t, W, Wh and Wy to denote larger quantities:

k	kilo-	10^3
M	mega-	10^6
G	giga-	10^9
T	tera-	10^{12}
P	peta-	10^{15}
E	exa-	10^{18}
Z	zeta-	10^{21}

Curriculum Vitae

Hal TURTON

Energy Program
and Special Project on Environmentally Compatible Energy Strategies
International Institute for Applied Systems Analysis (IIASA)
A-2361 Laxenburg, Austria

Tel: +43 2236 807 493, Fax: +43 2236 71313, Email: turton@iiasa.ac.at

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Hal Turton currently works at the International Institute for Applied Systems Analysis (IIASA) in Austria, which he joined in June 2003. His current research interests cover a range of areas including automobile technology assessment, security of energy supply, integrating energy and economic models, long-term scenarios and assessing the future role of hydrogen. Much of Mr Turton's dissertation work was conducted under the auspices of the Energy Economics group at the Paul Scherrer Institute at the ETH Zurich. He has previously been awarded degrees in public policy (MPubPol) from the Australian National University and advanced science (BSc (Hons) and the University Medal) from the University of New South Wales, Australia. Before joining IIASA, Mr Turton worked on energy and environmental policy research, analysis and development at a number of organisations in Australia from 1998 onwards. He has been a Research Fellow at The Australia Institute, and has also worked as a Policy Officer at the Greenhouse Policy Unit in the Victorian Department of Sustainability and Environment and the NSW Cabinet Office Greenhouse and Sustainable Development Unit, and as a Market Development Analyst at the Sustainable Energy Development Authority of NSW. His previous work at these organisations included research on the interactions between population policies and greenhouse gas emissions, carbon embodied in Australia's domestic trade, and assessing scenarios for achieving deep cuts in emissions.

Research interests in energy and climate policy

Automobile technology assessment, impact assessment of energy-related policies on climate change, security of energy supply, energy model development, bottom-up and top-down model integration, long-term scenarios and the role of hydrogen.

Academic Qualifications

Current: Enrolled in a doctorate course with the Energy Economics Group at the Paul Scherrer Institute of the Swiss Federal Institute of Technology, Zurich (ETH-Zurich). Thesis: *Scenario and policy analysis of sustainable energy systems and automobile transportation.*

1999: Master of Public Policy (majoring in Economics), Australian National University. Thesis: *The inflation-unemployment trade-off; do political institutions matter?*

1996: Bachelor of Science (Advanced, with Honours and the University Medal) in Molecular Genetics, University of New South Wales. Thesis: *Oxidative damage in* Saccharomyces cerevisiae. Scholarships and Prizes: University Medal, Australian Food Industry Science Centre Postgraduate Research Scholarship, Beckman Instruments Prize of the Biochemical Graduates Association, Honours Year Scholarship, Biological and Behavioural Sciences Scholarship, Molecular Simulations (Biosym Technologies) Prize, Biochemical

Graduates/Selby Scientific Prize, Inglis Hudson Bequest, Jeffrey Bequest, the Biochemical Graduates/Biotech International Prize, New College Academic Prize, University of NSW Co-op Scholarship,

1992: Year 12 Certificate, Hawker College, Australian Capital Territory
Tertiary Entrance Rank percentile: 99.30, Commonwealth Department of Education Prize

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Employment

2003/6 – current:
Research Scholar with the Energy Program and the Special Project on Environmentally Compatible Energy Strategies at the International Institute for Applied Systems Analysis (IIASA), Austria.

2002/10 – 2003/5:
Policy Analyst for the Greenhouse Policy Unit in the Victorian Department of Sustainability and Environment, Australia.

2001/7 – 2002/10 & 1998/7 – 1999/12:
Research Fellow (Energy, Climate Change and Environmental Policy) at The Australia Institute, an Australian non-government policy research organisation.

2000/1 – 2001/7:
Policy Officer and Market Development Analyst at the Sustainable Energy Development Authority of NSW, Australia. From June-December 2000, seconded to the Greenhouse and Sustainable Development Unit of the NSW Cabinet Office, Australia.

1998/2–6:
Intern with the Australian Federal Shadow Environment Minister, Hon. Duncan Kerr MP.

1995/12 –1996/2:
Research Scientist (with Vacation Scholarship) with Co-operative Research Centre for Food Industry Innovation, Australia.

1993/12 –1994/2:
Industrial Trainee, Shell Refining Australia Pty. Ltd., Sydney.

Research Publications and Presentations

Peer-reviewed journal articles:

Turton, H. & Moura, F. (2006). Vehicle-to-grid systems for sustainable development: an integrated energy analysis (submitted to *Technological Forecasting and Social Change*)

Moura, F. & Turton, H. (2006). Vehicle-to-grid power generation as a driver of energy system transformation (submitted to *Energy Policy*)

Ayres, R., Turton, H. & Casten, T. (2006). Energy efficiency, sustainability and economic growth, *Energy* (forthcoming)

Barreto, L. & Turton, H. (2006). Impact assessment of energy-related policy instruments on climate change and security of energy supply, *International Journal of Global Energy Issues* (forthcoming)

Turton, H. (2006). Long-term passenger transportation and car dependence in China (submitted to *Transportation Research: Part A*)

Turton, H. & Barreto, L. (2006). Long-term security of energy supply and climate change, *Energy Policy* 34:2232-2250

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Turton, H. (2005). ECLIPSE: an integrated energy-economy model for climate policy and scenario analysis (submitted to *Energy*)

Turton, H. & Barreto, L. (2005). Automobile technology, hydrogen and climate change: a long-term modelling analysis, *International Journal of Energy Technology and Policy* (forthcoming)

Hamilton, C. & Turton, H. (2002). Determinants of emissions growth in OECD countries, *Energy Policy* 30:63-71

Hamilton, C. & Turton, H. (1999). Population policy and environmental degradation: sources and trends in greenhouse gas emissions, *People and Place* 7(4):42-62

Evans, M.V., Turton, H.E., Grant, C.M. & Dawes, I.W. (1998). Toxicity of linoleic acid hydroperoxide to *Saccharomyces cerevisiae*: involvement of a respiration-related process for maximal sensitivity and adaptive response. *Journal of Bacteriology* 180(3):483-490

Turton, H.E., Dawes, I.W. & Grant, C.M. (1997). *Saccharomyces cerevisiae* exhibits a yAP-1-mediated adaptive response to malondialdehyde. *Journal of Bacteriology* 179(4): 1096-1101

International conference presentations:

Turton, H., Rao, S. & Sanderson, W. (2006). Determinants of energy demand: modeling and implications, Presentation at the IIASA Day on Energy, Laxenburg, 12 June

Schrattenholzer, L., Turton, H., Barreto, L. Jaskolski, M. & Miketa, A. (2005). The EU Energy Risk Landscape: Application of risk assessment methodologies for policy and technology support, Paper presented at the Safety & Security of Energy Infrastructures in a Comparative View (SEIF-CV) conference, 14-16 November 2005, Brussels, Centre La Borschette, organised by the Joint Research Centre of the European Commission

Sanderson, W. & Turton, H. (2005). Telling macroeconomic stories about SRES storylines: the case of China's future economic growth, Presentation at the IIASA Sources of Economic Growth Workshop, Laxenburg, 24-25 October

Turton, H. & Barreto, L. (2005). Climate change and security of energy supply: long-term synergies and trade-offs, Presentation at the International Energy Workshop 2005, Kyoto, 5-7 July

Korytarova, K., Hubacek, K. & Turton, H. (2004). CO_2 emissions from consumption in Slovakia, Paper presented to the 6th seminar on Environmental Economics, Policy and International Environmental Relations, Department of Economics, University of Prague, 7-8 October, ISBN 80-86709-05-1

Turton, H. & Barreto, L. (2004). Cars, hydrogen and climate change: a long-term analysis with the ERIS model, Paper presented to the 6th IAEE European Conference 2004 on Modelling in Energy Economics and Policy, Zürich, Switzerland, 2-3 September

Turton, H. & Barreto, L. (2004). The role of hydrogen and automobile technology in climate mitigation: a long-term analysis, Presentation to the International Energy Workshop 2004, Paris, 22-24 June

Reports and other papers:

Annema, J.A., Hoen, A., Turton, H., Schrattenholzer, L., Mudgal, S. & Fergusson, M. (2006), Scientific review of TREMOVE – a European transport policy assessment model, Report prepared under the Framework Contract with DG Environment of the European Commission on Economic Analysis in the Context of Environmental Policies and of Sustainable Development, ENV.G1/FRA/2004/0081, MNP report 500076003/2006 (forthcoming).

Turton, H. (2006). Impact of policy instruments on climate change and security of energy supply: a supplementary analysis for MINIMA-SUD, Report submitted to the EC-sponsored Methodologies for Integrating Impact Assessment in the Field of Sustainable Development (MINIMA-SUD) project, Contract No: EVG1-CT-2002-00082.

Turton, H. (2005). Measuring the impact of energy technology investment on long-term sustainability, Report to the EC-sponsored SAPIENTIA Project, Interim Report IR-05-038, International Institute for Applied Systems Analysis, Austria

Barreto, L. & Turton, H. (2005). Impact of alternative policy instruments on climate change and security of energy supply indicators: an analysis for MINIMA-SUD, Report to the EC-sponsored MINIMA-SUD Project, Interim Report IR-05-002, International Institute for Applied Systems Analysis, Austria.

Turton, H. & Barreto, L. (2004). The extended energy-systems ERIS model: an overview, Interim Report 04-010, International Institute for Applied Systems Analysis, Austria

Turton, H. (2004). Greenhouse gas emissions in industrialised countries; where does Australia stand? Discussion Paper 66, The Australia Institute, Canberra, June

Turton, H., Ma, J., Saddler, H. & Hamilton, C. (2002). Long-term greenhouse gas scenarios, Discussion Paper 48, The Australia Institute, Canberra, October

Turton, H. & Hamilton, C. (2002). Updating per capita emissions for industrialised countries, The Australia Institute, Canberra, August

Turton, H. (2002). The aluminium industry: structure, market power, emissions and subsidies, Discussion Paper 44, The Australia Institute, Canberra, February

Hamilton, C., Denniss, R. & Turton, H. (2002). Taxes and charges for environmental protection, Discussion Paper 46, The Australia Institute, Canberra, March

Hamilton, C., Turton, H. & Pollard, P. (2001). Climate change and Commonwealth nations, Discussion Paper 40, The Australia Institute, Canberra, October

Turton, H. & Hamilton, C. (1999). Population growth and greenhouse gas emissions: sources, trends and projections in Australia, Discussion Paper 26, The Australia Institute, Canberra

Hamilton, C. & Turton, H. (1999). Business tax and the environment: emissions trading as a tax reform option, Discussion Paper 22, The Australia Institute, Canberra

Quiggin, J., Saddler, H., Neutze, M., Hamilton, C. & Turton, H. (1998). The privatisation of ACTEW, Discussion Paper 20, The Australia Institute, Canberra

Turton, H. & Hamilton, C. (1998). The GST package and air pollution, Discussion Paper 19, The Australia Institute, Canberra

Turton, H. (1998). International greenhouse gas emissions trading: participation by Australia, Report to the Shadow Environment Minister, Australian National Internships Program, ANU, Canberra