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Global Hydrogen and Electricity Storylines

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Global Scenarios for the Energy Infrastructure Development

1. Summary

The basic motivation for undertaking the development of alternative storylines about future diffusion of new energy infrastructures is the need for a transition of the global energy system toward (1) provision of affordable and reliable energy services for most of the global population and (2) protection of the environment at all scales from global to local. Another salient energy challenge that needs to be considered in this context is the issue of supply security. A complete paradigm change is required for this transition to take place. An important dimension of this change is the development and widespread deployment of hydrogen and electricity systems toward zero-emissions energy systems. Such a transition toward a *hyd*rogen and electr*icity* (hydricity) age is consistent with the historical evolution of global energy system.

It is consistent with a pervasive decarbonization of energy end use from exclusive dependence on carbon-intensive energy carriers such as direct use of coal and biomass toward liquid energy carriers, electricity and energy gases. These developments of energy end use also reflect similar changes in the nature of energy supply. Primary energy structure has decarbonized as well, from reliance on traditional energy sources and coal toward ever-larger shares of oil, gas, nuclear and modern renewables.

Energy gases have an especially important role as they offer the possibility of grid-oriented and very convenient energy carriers, ranging from syngases to methane and hydrogen. They complement electricity as the other grid-oriented and also very convenient energy carrier. A further shift toward energy gases and electricity and eventually also toward the hydricity age is consistent with increasing quality and flexibility of energy carriers, higher security and better environmental protection. It is also consistent with increasing share of grid-oriented energy carriers reaching the consumer today in the more affluent parts of the world primarily as natural gas and electricity. All of such future changes will necessitate development of pervasive energy infrastructures. Some of these infrastructures may be global and integrated, others more local and regional.

What is fundamentally new about the current dependence on fossil energy sources is that for the first time humanity is in the position to irreversibly interfere in the planetary processes from ecosphere to climate change. This is a reason why the Nobel laureate Paul Crutzen suggested the present era be called Anthropocene (Steffen *et al.*, 2004a and 2004b). Here again energy gases and hydrogen jointly with electricity hold the promise of bridging the challenge of both higher quality of energy services and minimal environmental burdens. The essential advantage is the hydricity technologies could offer future energy systems with zero carbon emissions provided that both electricity and hydrogen are produced from hydrocarbons with carbon capture and storage or from other sources of energy such as nuclear and new renewables.

The main challenge in describing possible evolutionary or more abrupt paths toward the hydricity age is that this transition is likely to occur on the scale of a century or longer. The basic scenario is that electricity and energy gases, first natural gas and later

hydrogen, would gradually replace solid and liquid fuels. Hydrogen, while making inroads before 2050, would predominate only beyond and become the main energy carrier toward the end of the century. Even if a full transition toward the age of hydricity is achieved, there are many possible development paths from the present toward this distant future, there are many alternative energy systems that convert primary energy sources to emissions-free hydricity carriers, from fossils in conjunction with carbon capture and storage, to nuclear and new renewables.[1]

The future is inherently unpredictable. The challenge in developing scenarios and their narratives is to provide a "grand logic" how major developments toward hydricity age might take place, what are their implications for policies and measures, what are other salient enabling developments and so on. Here we choose two basic narratives to tell two alternative stories of future transitions toward the hydricity age. They differ in numerous ways but we will provide some quantitative illustrations of their concurrences and differences. They are not merely two branches of one possible future but two fully alternative development paths with some shared characteristics. For example, we assume different rates of economic and social development, different institutional and geopolitical characteristics, alternative directions of research and development of new technologies as well as different technological investments and priorities, different future resource endowments (to a degree a function of technology), lifestyles, dietary preferences, settlement patterns and so on. Clearly, it will not be possible to outline in detail all of these different developments in this kind of an overview report, but we will try to provide salient illustrations of both the narrative and quantitative characteristics of the two narratives.

There are also important similarities and concurrences in the two storylines. They share a common demographic development characterized with a successful transition toward low fertility rates, both represent affluent future worlds with adequate and affordable provision of energy services for virtually all. Finally, both assume sufficient investment in innovations and their diffusion so as to empower the transition toward new development paths leading toward the hydricity age.

One of the two storylines, simply called A1H&E, specifies more emphasis on the centralized energy conversion, distribution and end-use patterns. It is an urbanized world with much of the land "given back" to the nature. Humanity is concentrated predominantly in large urban corridors and mega-settlement patterns. Current examples would be the Tokyo-Osaka corridor, the Ruhr cluster in Europe, the eastern seaboard in the US and many of the main mega-cities in the developing parts of the world ranging from Delhi, Beijing and Mexico City to Sao Paolo. Such settlement patterns could emerge in the future across the Trans-Siberian Corridor and elsewhere in Asia, Africa and Latin America. They may become more focused in the "North" today but are not all that likely to expand massively due to the aging and declining population trends. A1H&E storyline implies massive infrastructural developments in particular in the now developing parts of the world. In the energy area this implies development of large sources of primary energy, integrated grids from electricity and pipelines to cryogenic

[1] Strictly speaking, there will be some residual emissions from practically any energy system. For example, carbon capture is never complete and storage can leak, many renewables such as biomass, hydropower and geothermal lead so some greenhouse gas emissions, while all energy systems lead at least indirectly to some emissions, e.g. because of the cement demand and possible also some fossil energy needs on the total life-cycle basis.

networks for energy gases. Most of the conversion and transformation would be central providing very flexible and environmentally benign structures of energy end use. Lifestyles are likely to change fundamentally in this future world as time progresses, especially toward the end of the century, but this version of the hydricity age story is in principle consistent with current lifestyles and settlement patterns of the most affluent parts of the world.

The other storyline, simply called B1H&E, specifies more emphasis on decentralized energy conversion, distribution and energy end-use patterns. The world is also more urbanized than today but the patterns are assumed to be fundamentally different. They would be more consistent with widespread of urban sprawl into smaller settlements and communities. These are also interconnected through sophisticated infrastructures, but are fundamentally more autonomous and autarkical. The scenario places great emphasis on environmental protection at all scales, from local to global. It is representative of a successful implementation of sustainability together with a more equitable society. This implies that there is a substantial degree of income redistribution in space and time (another important maxim of the sustainability transition). As such, the scenario illustrates a complete paradigm change compared to current inequalities and environmental destruction. Another salient aspect of this scenario is the implicit change in lifestyle and social priorities.

The two scenarios both draw on current tendencies in the world. They merely amplify these tendencies in different directions. A1H&E toward vigorous economic development that leads to leapfrogging of those left behind today, but also unprecedented affluence of the rich. It is associated with high rates of capital turnover, generous investment in research and innovations, infrastructures, education, cultural values and social security for the less privileged. B1H&E amplifies current tendencies toward stronger environmental awareness and harmony with nature, on global redistribution of income toward higher equity, decentralized governance and sustainability across all scales. They both also include elements of each other. In a nutshell, the difference is in emphasis. Nevertheless, they lead to alternative development paths toward the hydricity age and to fundamentally different future energy systems and end-use patterns.

This translates in important characteristics of the future energy systems and hydricity age. Both scenarios outline a paradigm shift toward massive decarbonization. A1H&E achieves this transition through integrated infrastructures and centralize energy supply with vigorous conversions systems and trade across the globe. B1H&E relies more on decentralized energy generation and end use. A1H&E is more consistent with large-scale systems such as continental and global hydricity grids, decarbonization of fossil energy sources and geological carbon storage, nuclear power and centralized hydricity generation from large-scale renewables such as wind and solar. B1-H&B is more consistent with community-scale energy systems based on local renewable sources and more modest decarbonization of fossil energy sources as well as small nuclear facilities without a full fuel cycle. However, both scenarios include all options, none has a “silver bullet” that resolves all energy challenges.

2. Purposes of Scenarios

2.1. What are Scenarios?

Scenarios are descriptions of possible future developments. They are *visions* of how main driving forces underlying the salient future developments might evolve and interact with each. They are also visions of what such developments might imply about possible future states and how the near-term decisions might affect these. Scenarios are context specific. How they are developed and used depends very much on what the main purpose is and what are the main questions they are intended to inform. Our main question and purpose of the two hydricity storylines is seemingly simple: How do two alternative development paths toward hydricity age look like and how might they be achieved (Nakicenovic *et al*., 2000).

Future is inherently unknown. Scenarios cannot be and are *not predictions* of future developments. Hydricity storylines are not projections of past trends either. Instead, they describe possible futures. Often scenarios come as a set of alternatives. Here we outline two storylines.

Another purpose of the scenarios is to provide a framework for decision-making and to help illuminate the impacts associated with alternative courses of action. Scenarios facilitate the interpretation of possible consequences of these actions on future states.

A further important characteristic of the scenarios is that they often include elements of future developments that cannot be formally modeled. For example, in the energy area they may specify lifestyle changes that comprise still a very elusive element in models. In many cases, the scenarios systematically follow through a number of assumptions and assess implications of policies and measures currently discussed by decision-makers around the world. Finally, perhaps the most important element of scenarios is that they challenge the prevailing mindsets.

There are many definitions of scenarios in the literature. They differ a lot depending on the purpose of the scenarios and how they were developed. For example, the Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) by the Intergovernmental Panel on Climate Change (IPCC) defines a scenario as a plausible description of how future might develop, based on a coherent and internally consistent set of assumptions (“scenario logic”) about the key relationships and driving forces (e.g. rate of technology changes or prices).

Generally, the scenarios do not attempt to describe all possible futures that can be imagined. Alternative scenario paths are developed to provide plausible answers to the major uncertainties and focal questions about the future of socioecological systems. In this particular case, we consider two related, but alternative development paths that might lead toward the (*hyd*rogen and elect*ricity*) hydricity age. We do not consider all possible future development paths that might lead to a wider role of hydricity technologies and systems. Instead, we consider two alternative futures; one with more emphasis on decentralized systems and the other with more emphasis on centralized ones. They differ in emphasis and do not mutually exclude each other. Rather, they amplify differently some of the common development tendencies. They are stylized and not fully quantified.

2.2. Types of Scenarios

Scenarios range from quantitative ones developed by models to narrative stories. Figure 2.1 illustrates this continuum of different scenarios in the underlying literature. Recently, a major methodological advance in scenario formulation process includes approaches that integrate narrative stories with quantitative model-based analysis. The hydricity storylines were developed in the context of this major advance in the methodology of scenario analysis. Here we focus on two narrative stories of how hydricity age might emerge. They are modified version of two storylinespresented in the Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) by the Intergovernmental Panel on Climate Change (IPCC). The original IPCC scenarios include four storylines and alternative model quantifications of these storylines that resulted in 40 scenarios.

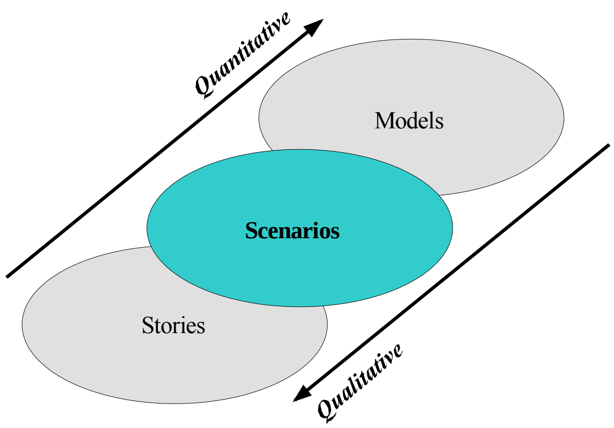


Figure 2.1: Schematic illustration of alternative scenario formulations, from narrative storylines to quantitative formal models. Source: Nakicenovic et al., 2000.

Figure 2.2 shows a typology for assessment based on the distinction made by Rayner and Malone (1988) between descriptive social science research based on an analysis of mostly quantitative energy and material flows, and interpretive social science, focused on the values, meaning, and motivations of human agents (Rayner and Malone 1988; see also Robinson and Timmerman 1993). The figure further distinguishes between more global and more local analysis, and attempts to indicate typical forms of analysis that correspond to the four quadrants thus identified. The distinctions among the quadrants shown in Figure 2.2 underlie many of the problems of interdisciplinary communication and analysis in the sciences. It is well known that it is difficult to combine, for example, interpretive place-based analysis of human motivations with, say, a quantitative analysis of energy systems and emissions. For example, it has been notoriously difficult to include life-style changes in the evolution of energy end use and services. Much of the early work in the climate and energy fields, whether global or local, was located on the descriptive side of the typology.

It is particularly noteworthy therefore, that recent developments in scenario analysis are beginning to bridge this difficult gap (Morita *et al.* 2001, Swart *et al.*, 2004, and Millennium Ecosystems Assessment scenarios (MA, 2005). Over the past decade, the global scenario analysis community has begun to combine the primarily qualitative and narrative-based scenario analyses undertaken by Royal Dutch/Shell and other companies (Wack 1985a; Wack 1985b; Schwartz 1992), with global modeling work in the form of analyses that combine the development of detailed narrative storylines with their "quantification" in various global models (Raskin *et al*., 1998; Nakicenovic *et al.,* 2000). For example, the SRES (Nakicenovic *et al.* 2000) work, undertaken for the IPCC, cut across the interpretive/descriptive divide (See Figure 2.2), though still focusing mainly on the global and regional level. As illustrated in Figure 2.1, the hydricity storylines also cuts across the divide between interpretive and descriptive research by combining narrative storylines and quantitative modeling. The hydricity storylines are rooted in the original SRES ones.

	Local	**Global**
Interpretive	Place-based case studies	Global storylines
Descriptive	Regional science	Global modeling

Figure 2.2: Analytical typology of scenarios analysis. This figure illustrates local and global scenarios exercises that are more based on interpretive, qualitative or descriptive storyline-based approaches. Source: Nakicenovic et al., 2005.

Another new development in scenarios is to reach across the global/local gap, with a stronger focus on local analysis of energy systems and services or ecosystems and its services (e.g. Carpenter *et al*., 2005). This could be accomplished in future assessments of hydricity systems and their emergence by incorporating information from sub-global assessments (e.g., for Europe, North America or Asia) in the global scenario effort and vice versa. Also, a few methodological improvements could be explored by linking and/or nesting the development of the local, regional, and global scenarios. Linking and nesting different scale scenario exercises will be a field that needs further exploration in the future. In this way, the future work on hydricity storylines could contribute to the trend toward more integrated and more interdisciplinary work on the relationships among human and natural systems. The hydricity storylines presented in this study are primarily global, but the next step in the development of the storylines and the fully-fledged scenarios could go one step further in the direction of developing multi-scale scenarios, both in time and space.

2.3. Hydricity Storylines

Figure 2.3 demonstrates the place of the hydricity storylines along two axis describing the geographical scale of work and the degree to which the scenarios are based on interpretive, qualitative storylines or grounded in model-based descriptions. The hydricity scenarios combine the storyline approach with a previous quantification of the original SRES scenarios. The storylines have been conceived and developed to provide insights into a broad range of potential future energy-systems changes. The objective was to portray plausible developments that are internally consistent, rather than those that may be considered to be desirable on undesirable. The idea of what is "negative" or "positive" in any given scenario and its associated storyline is inherently dependent on the eye of the beholder and thus highly subjective. Clearly, hydricity technologies hold the promise of many benefits (positive) and the tread of many dangers and risks (negative). Therefore great attention was given in this study to present both positive and negative aspects in the storylines. Uniting only "positive" or "negative" features in a scenario would result in homogeneous and "uni-dimensional" futures that may not be plausible and consistent. We have refrained from setting up either of the two storylines as either positive or negative. Instead, elements of both are present in the two storylines.

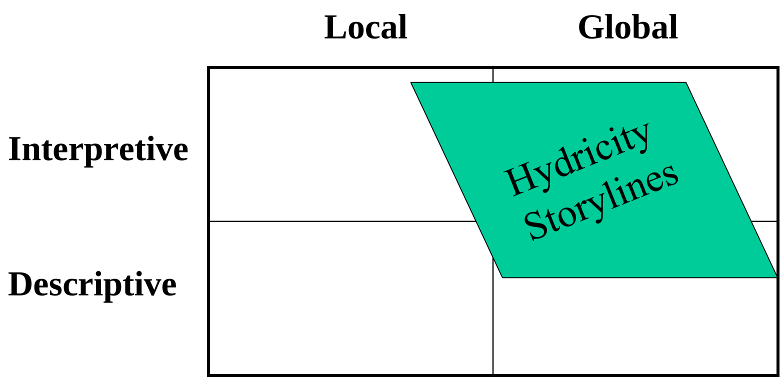


Figure 2.3: Illustrative placement of hydricity storylines in analytical typology given in Figure 2.2. The storylines are primarily interpretive and qualitative but are rooted in the descriptive and quantitative SRES scenario families. They give little local and regional context and focus primarily on global developments. Source: Based on Nakicenovic et al., 2005.

It can be argued that the narrative storylines are richer than quantitative scenarios (whether model based or not) in the sense that they can provide seemingly seamless connections across multitudes of scales, but compared to numerical and analytical models, they are not quantitative and do not provide reproducibility under varying assumptions about main driving forces.

The combination of narrative *storylines* and their *quantification* in integrated scenarios of alternative futures is the main method for capturing complexity and uncertainty and transcending limits of conventional deterministic models of change. The hydricity storylines address a highly complex set of interactions between human and natural systems, a scientific challenge that is compounded by the cumulative and long-term character of the phenomena. While the world of many decades from now is indeterminate, storyline-based scenarios offer a structured means of organizing information and gleaning insight into the possibilities. Scenarios can draw on both science and imagination to articulate a spectrum of plausible visions of the future and pathways of development. Some characteristics of the hydricity scenarios are assumed to evolve gradually and continuously from current social, economic, and environmental patterns and trends; others deviate in fundamental ways. A long-term view of a multiplicity of future possibilities is required in order to be able to consider the ultimate risks of maintaining adequate energy services, assess critical interactions with other aspects of human, technological and environmental systems, and guide policy responses (MA, 2005).

The development of methods to effectively blend quantitative and qualitative insights is at the frontier of scenarios research today. The narrative storylines give voice to important qualitative factors shaping development such as values, behaviors, and institutions, providing a broader perspective than is possible by analytical and numerical modeling alone. Storylines are rich in detail, texture, metaphors, and possible insights, while quantitative analysis offers structure, discipline, rigor, and reproducibility. The most relevant recent efforts are those that have sought to balance these attributes. They provide important insights into how current tendencies and trends might become amplified in different future worlds across the four storylines and provide a multitude of different details across scales and systems. They are embedded in extensive assessment of the main driving forces and their future developments across scenarios in the literature.

Multiple futures are fundamental to any scenario enterprise, because prediction of complex and evolving systems is not possible. They are required for indicating the range of plausible futures and for encompassing some of the deep uncertainties associated with the evolution of complex systems. Examples of deep uncertainties are non-linear responses of complex systems, emerging properties and path dependencies, and generally unpredictable behavior that emerges due to branching points, bifurcations, and complex temporal and spatial dynamics. Complex systems are inherently unpredictable, especially when human response strategies that have yet to be defined are involved. It is likely that the long-term evolution of energy as one of many complex systems shaping our future will unfold in unexpected ways and will embody important surprises. Such surprises could include unexpected emergent properties, path dependencies, and the crossing of critical thresholds, leading to irreversibilities.

The overall time horizon of the hydricity age reaches well beyond 2050. This is the case because of sheer inertia of the global energy system. It will remain to be predominately fossil based over many decades to come. The shift toward more convenient and less polluting energy carriers is likely to be an equally long process. Thus, long time horizons are required to encompass fundamental changes in anthropogenic, technological and ecological systems and their interactions. Interaction with many Earth systems across different scales might involve even longer time periods. These processes certainly have time scales much longer than a century. It can be argued that some aspects of technological and social systems also need much longer time frames; the hydricity era might be initiated during the 21st century as indicated by the two storylines, but it would certainly not denote the dominant paradigm and if it ever does than most likely only toward the end of the century.

Given the modest modeling techniques available today (especially in the area of integrated assessment), development of a rich set of alternative scenarios is the main method used to encompass these different possibilities and the associated uncertainties. This approach is also followed in the two hydricity storylines. In addition to the quantitative formulation of many of the alternative scenario characteristics with a set of six integrated assessment models (IAM) in the original SRES scenarios, the two hydricity storylines have elaborate narratives that extend beyond the scenario quantifications and extend across a multitude of levels and scales. They provide the background information about the main driving direct forces, the associated fundamental drivers, and their consequences.

3. Storylines and Scenarios

3.1. SRES Storylines and Scenarios

The two hydricity storylines, and especially their quantifications, are deeply rooted in two of the four SRES scenario families. The SRES emissions scenarios are based on an internally consistent and reproducible set of assumptions about the key relationships and driving forces of change, derived from the analysis of both historical developments and the current situation. The SRES scenarios consist of both qualitative and quantitative components; they have narrative storylines and a number of corresponding quantitative scenarios for each storyline developed by six different IAMs (Nakicenovic *et al.*, 2000). This way the four storylines multiplied into 40 emissions scenarios. In addition, a set of scenarios that lead to the stabilization of atmospheric carbon concentrations have been developed for the IPCC Third Assessment Report (TAR). They were derived by nine different IAMs (Morita *et al.*, 2001) for different stabilization levels leading to some 80 distinct stabilization scenarios.

Here we have extended two of the SRES storylines to incorporate two alternative paths toward the hydricity age. This involved extensions of the original storylines to include the emergence of the hydricity age. The new storylines build also on some of the SRES scenarios (based on different models). The primary quantifications are those of stabilization scenarios. The reason is simply that climate mitigation requires drastic decarbonization of energy and hydricity technologies are some of the most important options to achieve this.

The SRES scenarios are descriptive and were not intended to be prescriptive. Even the stabilization cases do not prescribe specific mitigation policies but rather assess what measures would be required to achieve drastic reduction of emissions. They are neither desirable nor undesirable in their own right. Thus, they are consistent with the notion that scenarios need not be generally “positive” or “negative”. They have been built as descriptions of plausible alternative futures, rather than preferred, developments. The same characteristics have been incorporated in the two hydricity storylines.

The SRES scenarios are grouped into four scenario families (simply called A1, A2, B1, and B2). Each family differs with respect to many of its main driving forces and the resulting characteristics ranging from the demographic, economic, technological development patterns and pathways to the resulting energy requirements and emissions. Figure 3.1 gives a schematic illustration of the four scenario families, very simplistically, as branches of a two-dimensional tree. In reality, the four scenario families share a space of a much higher dimensionality given the numerous assumptions needed to define any given scenario in a particular modeling approach. The schematic diagram illustrates that the scenarios build on the main driving forces of GHG emissions. Each scenario family is based on a common specification of some of the main driving forces.

Box: History of SRES Scenarios

In 1992, IPCC developed a set of six emissions scenarios. In 1996, after evaluating the usefulness of the 1992 scenarios (Alcamo *et al.*, 1995), the IPCC decided to develop a new set of emissions scenarios, the SRES scenarios (Nakicenovic *et al.*, 2000), which are used as baseline scenarios in developing the hydricity storylines.

The SRES writing team developed 40 individual scenarios based on an extensive literature assessment, based on six alternative modeling approaches, and an "open process" that solicited wide participation and feedback. They cover a wide range of the main demographic, technological and economic driving forces for GHG and sulfur emissions. These scenarios do not include explicit mitigation measures or policies (additional climate policy initiatives), although they necessarily encompass various policies of other types, some of which have the effect of reducing emissions. In TAR, IPCC developed an additional set of 80 concentrations stabilization scenarios based on SRES. They include a wide spectrum of emissions mitigation measures and polices.

Each scenario links one of four narrative "storylines" with one particular quantitative model interpretation. All the scenarios based on a specific storyline constitute a scenario "family". The following Box summarizes four narrative storylines, which describe driving forces of SRES scenarios and their relationships. Each storyline represent the playing out of different social, economic, technological and environmental developments (or paradigms), which may be viewed positively by some people and negatively by others. Possible "surprise" and "disaster" scenarios were excluded.

Six different models, AIM, ASF, IMAGE, MARIA, MESSAGE-MACRO and MiniCAM were used to develop 40 SRES scenarios. These models are representative of different modeling approaches ranging from macroeconomic to systems-engineering models and different integrated assessment frameworks in the literature such as those that focus more on land-use and other more on energy systems changes. Table 3.1 summarizes the main demographic, economic and energy driving forces for A1T and B1T SRES scenarios with MESSAGE IAM that provide the basis for the two hydricity storylines, A1H&E and B1H&E. These drive the energy-systems and land-use changes that are the major sources of GHG emissions.

Table 3.1 indicates that the two scenarios share almost identical population projections that lead to about nine billion by 2050 and declines to below eight billion people by 2100. Both scenarios lead to very high rates of economic development leading to conditional catch-up of the developing parts. It is noteworthy that rapid development leads to a high rate of capital turnover in both scenarios. This means that most efficient technologies replace older vintages leading to high rates of energy efficiency improvement especially in the end use (e.g. final energy intensity) and thus relatively low levels of primary energy requirements. Generally, scenario A1 portrays higher rates of growth and energy efficiency improvement, while scenario B1 leads to more drastic change of lifestyles and human behavior toward energy efficiency improvements.

Table 3.1: Overview of main scenario driving forces in 2020, 2050 and 2100. Numbers show the main driving forces of A1T-MESSAGE and B1T-MESSAGE scenarios that provide the basis for the two hydricity storylines A1H&E and B1H&E. Units are given in the table. Source: Nakicenovic et al., 2000.

	1990	**A1T**	**B1T**
Population (billion)	5.3		
2020		7.6	7.6
2050		8.7	8.7
2100		7.1	7.7
World GDP (10^{12} 1990US$)	21		
2020		57	52
2050		187	136
2100		550	290
Income ratio North to South (Annex-I to Non-Annex-I)	16.1		
2020		6.4	8.1
2050		2.8	3.4
2100		1.7	1.5
Final energy intensity (10^6J/US$)[a]	16.7		
2020		8.7	8.6
2050		4.8	4.5
2100		2.3	1.4
Primary energy (10^{18} J)[a]	351		
2020		649	583
2050		1213	516
2100		2021	714

These are two out of 40 SRES scenarios that represent “successful” future development path. They provide a good platform for the two hydricity storylines both because rapid development is based on vigorous diffusion of new technologies and frequent capital turnover. This propensity to innovate is consistent with possible emergence of a hydrogen economy in the distant future.

In contrast to these two scenarios, the compete set of all 40 SRES scenarios cover most of the range of carbon dioxide, other GHG, and sulfur emissions found in the recent scenario literature. A1 and B1 scenarios are in the lower range of population growth, higher range of economic development rates as well as energy improvement rates.

Appendix 1a and b summarizes main demographic, technological, social and economic driving forces across the SRES scenarios and the resulting GHG and sulfur emissions of the scenarios at 1990, 2020, 2050, and 2100 year. CO_2 emissions in A1 are highest in growth rate in the first quarter of the 21st century, peak at the middle of the century in terms of absolute emission levels, and then decrease toward 2100. In A2, CO_2 emissions are in the middle of the range of scenarios in the first half of 21 century, but become very high in the latter half of the century. In the B1 world, CO_2 emissions decline after the second quarter of the 21st century even without any climate policy, and this scenario family has the lowest emission levels in the latter half of the century. CO_2 emissions in B2 world are lowest in the first half of the 21st century, but continue to increase in the second half, and the emissions reach a similar level to that in A1 in 2100.

Box: The main characteristics of the four SRES storylines and scenario families. Storylines A1 and B1 are used as the basis for the hydrogen and electricity narratives in this report.

The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are convergence among regions, capacity building and increased cultural and social interaction, with a substantial reduction in regional differences in per capita income.

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in high population growth. Economic development is primarily regionally-oriented, and per capita economic growth and technological change are more fragmented and slow compared to other storylines.

The B1 storyline and scenario family describes a convergent world with rapid change in economic structures toward a service and information economy, reduction in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with less rapid, and more diverse technological change, but with a strong emphasis on community initiative and social innovation to find local and regional solutions. While policies are also oriented towards environmental protection and social equity, they are focused on local and regional levels.

With its high rate of economic growth, futures in the A1 family generate great pressures on the energy resource base. As a result, this set of scenarios has a particularly large level of uncertainty with regard to the future directions of technological progress in general and especially in the energy field. This is the reason why the A1 scenario family is divided into *three scenario groups* that are each based on alternative directions of technological change in the energy system: A1FI, A1T and A1B scenario groups.

The A1FI scenario group is fossil-fuel intensive and includes two fossil fuel dominated alternatives: A1C (coal intensive) and A1G (oil and gas intensive). A1C scenarios are based on "clean coal" technologies that are generally environmentally friendly with exception of the fact that they have high GHG emissions. A1G scenarios describe "oil- and gas-rich" futures, with a swift transition from conventional resources to abundant unconventional resources including methane clathrates (hydrates). The A1T scenario group ("new-energy technology" – intensive) is characterized by rapid development of solar and nuclear technologies on the supply side and fuel cells used in energy end-use applications. A1B is balanced across all energy sources. 'Balanced' is defined as not relying too heavily on one particular energy source and incorporates the assumption that similar improvement rates apply to all energy supplies and end-use technologies. The "snowflake" diagram in Figure 3.2 indicates the ranges of the main driving forces and the resulting emissions across scenarios sharing the A1 storyline.

SRES Scenarios

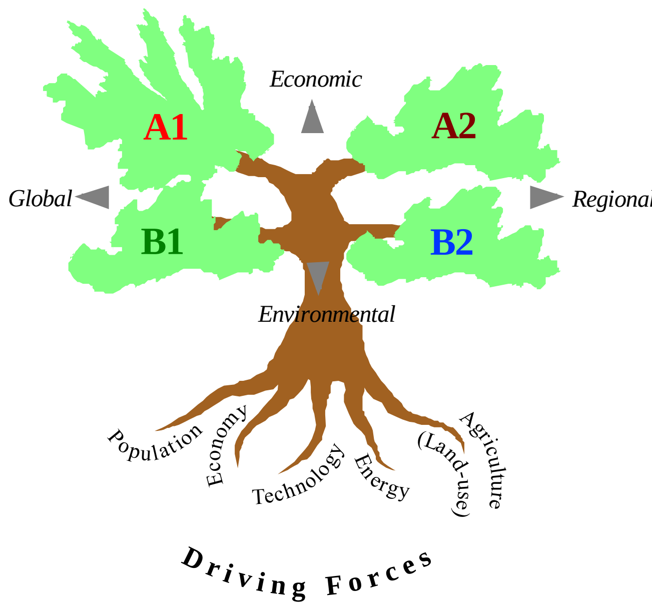


Figure 3.1: Schematic illustration of SRES scenarios. The four scenario "families" are illustrated, very simplistically, as branches of a two-dimensional tree. In reality, the four scenario families share a space of a much higher dimensionality given the numerous assumptions needed to define any given scenario in a particular modeling approach. The schematic diagram illustrates that the scenarios build on the main driving forces of GHG emissions. Source: Nakicenovic et al., 2000.

The A2 scenario family represents a differentiated world with high population growth, relatively slow GDP per capita growth, relatively high energy use, and slow technological change. The high population growth leads to some 14 billion people by the end of the century. This is expected to create many pressures worldwide especially during the coming decades and present an obstacle to development. For example, ASIA's population would continue to grow throughout the 21st century, exceeding 7 billion by 2100. More recent high population scenarios are significantly lower, especially in Asia, resulting in global populations of some 12 billion. This kind of high population growth resulting from a delayed fertility transition would, combined with the internationally more fragmented economic and technological outlook result in comparatively modest income levels (below $10,000 per capita by 2100). Energy use, while lower than in the A1 scenario family would nonetheless remain comparatively high, exceeding with 470 EJ *current* global energy use by 2100. Figure 3.2 indicates the ranges of the main driving forces and the resulting emissions across scenarios sharing the A2 storyline.

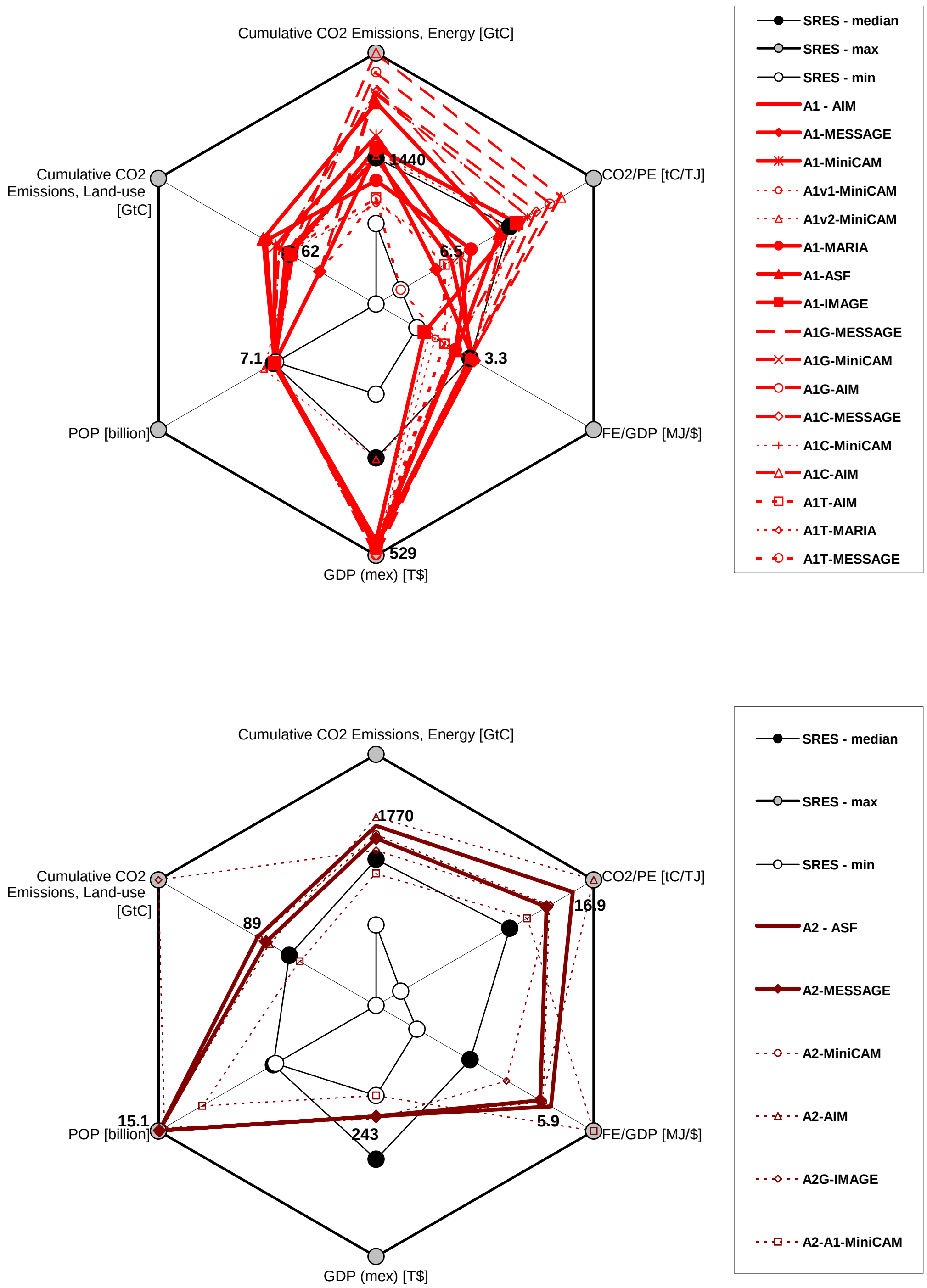


Figure 3.2: Global cumulative CO_2 emissions in the A1 and A2 scenarios and their main driving forces. The minimum, maximum and median (50^{th} percentile) values shown on the six axes of each hexagon, for the cumulative energy and land-us CO_2 emissions from 1990 to 2100 and 2100 values for the four driving forces, are based on the distribution of scenarios in the literature. Source: Nakicenovic et al., 2000.

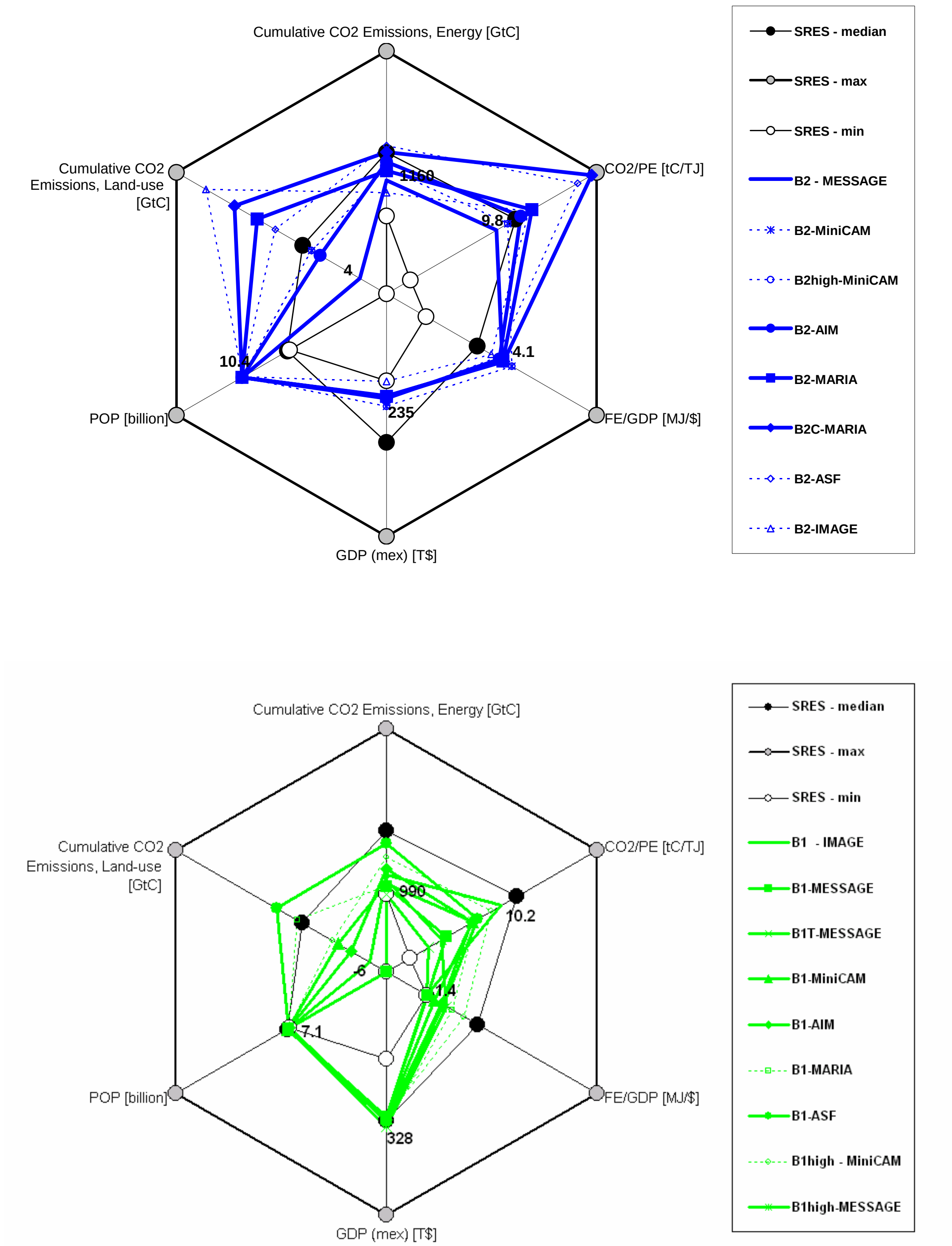


Figure 3.3: Global cumulative CO_2 emissions in the B1 and B2 scenarios and their main driving forces. The minimum, maximum and median (50^{th} percentile) values shown on the six axes of each hexagon, for the cumulative energy and land-us CO_2 emissions from 1990 to 2100 and 2100 values for the four driving forces, are based on the distribution of scenarios in the literature. Source: Nakicenovic et al., 2000.

The B1 scenario family describes a world with low population growth, rapid changes in economic structures toward a service and information economy, reduction in material intensity and the introduction of clean and resource-efficient technologies, paraphrasing an overall sustainable development theme. Population developments would be similar to the A1 scenario family, however combined with drastically lowered resource use (some 200 EJ primary energy use by 2100). Incomes are very high, but lower compared to A1 scenario family. However, B1 is much more equitable world with high levels of international collaboration and solidarity and unprecedented levels of environmental awareness. This results in very low adverse interferences with Earth systems. The B1 scenarios are more sustainable than those of the other three families. The "snowflake" diagram in Figure 3.3 indicates the ranges of the main driving forces and the resulting emissions across scenarios sharing the B1 storyline.

Finally, the B2 scenario family represents a world in which the emphasis is on local solution to economic, social and environmental sustainability. This world is characterized by moderate population growth, intermediate level of economic development and less rapid and more diverse technological change than in A1 and B1 scenario storylines. Figure 3.3 indicates the ranges of the main driving forces and the resulting emissions across scenarios sharing the B2 storyline.

The stabilization scenarios bear the same main scenario driving forces as the corresponding no-climate policy, "baseline" SRES scenarios, but differ in levels of energy demand and especially in their energy supply structures (and to a lesser extent also in land-use practices) as a result of emission constraints leading to a stabilization of atmospheric CO_2 at alternative levels ranging between 450 to 750 ppmv. Some 80 different stabilization (here called Post-SRES) scenarios were developed by nine different IAMs for IPCC TAR (Morita *et al.*, 2001), all based on the 40 SRES baseline scenarios. Even though SRES scenarios include enormous technological advances and structural change in the energy system, the Post-SRES are characterized by even more fundamental paradigm change in the energy system toward zero emissions. This means that hydrogen and electricity have even larger roles in these scenarios compared to the SRES baselines.

3.2. Energy Systems Structures in SRES Scenarios

There are a number of energy challenges for the 21st century. As mentioned, the first challenge is that about one third of the global population, or some two billion people, do not have access to affordable and clean energy services and need to be "connected" to reliable and affordable sources of energy. These are often the same people who do not have access to clean water or sanitation and are, in general, deprived from adequate access to many other essential amenities. Because of the dangers of climate change, it follows that the access to energy services cannot be provided exclusively by now predominant ways of converting hydrocarbon sources into electricity and fuels.

The second challenge is how developing countries can leapfrog some traditional development phases and directly adopt the newest practices and technologies. This is exceptionally difficult to achieve in the view that technology adoption and diffusion is historically a long process, especially in the case of energy-related infrastructures.

Historically, it has taken between 20 years to half a century and more for new technologies to substitute the old ones. In other words, time itself is a limited resource.

A further challenge is finding the means to finance the energy investments that are required for achieving these transformations in a world where ODA (official development aid) and FDI (foreign direct investment) are already falling short of the development needs. Total global investments in energy infrastructures and systems to achieve such a transition toward adequate provisioning of energy services is estimated at some $300 to 500 billion per year during the next 20 years (WEA, Goldemberg *et al.*, 2000). A substantial part of these large investment requirements would be for the development of energy infrastructures. The estimated investment requirements correspond to some ten percent of total global investment indicating again the magnitude of such a challenge. Finally, perhaps the biggest challenge from today's perspective is how to combat the adverse impacts of energy systems across all scales, from local indoor air pollution all the way to climate change. However, to achieve a sustainability transition, all of the above challenges need to be faced and resolved.

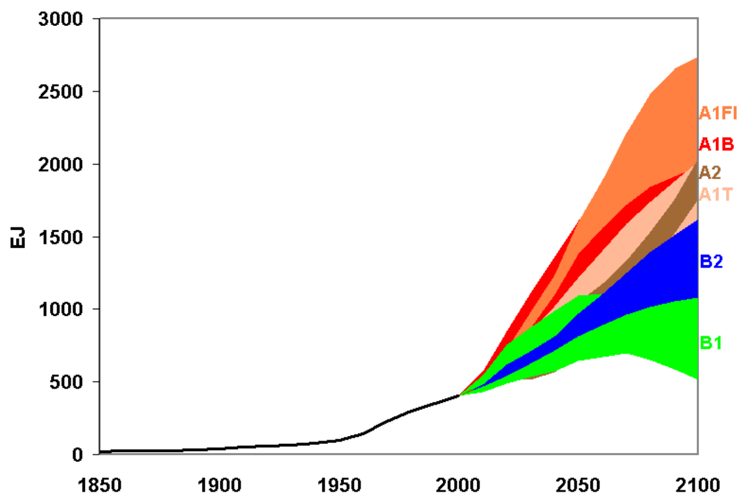


Figure 3.4: Global primary energy requirements since 1850 and in the IPCC SRES scenarios to 2100 in EJ per year. Source: Nakicenovic et al., 2000.

Thus, a prerequisite for achieving further economic development in the world are adequate levels of energy services. Figure 3.4 compares future energy requirements across a wide range of SRES scenarios (Nakicenovic *et al.*, 2000) with the historical development. Since the beginning of the industrial revolution, global primary energy has grown at about two percent per year. The SRES scenarios indicate a seven-fold increase in primary energy requirements at the high end of the scale and at least almost a two-fold increase at the low end. What is interesting to note is that the scenarios in the lower range represent sustainable futures with a transition to very efficient energy use and high degrees of conservation that result in a radical departure from the current development paths. Generally, these are also the scenarios in which energy sources with low carbon intensity play an important role leading to vigorous reduction of future GHG emissions. SRES scenarios in this lower part of the range include substantial decarbonization of the energy system and vigorous diffusion of electricity and hydrogen.

Figure 3.5 illustrates alternative energy systems structures across the range of scenarios. Relative shares of different energy sources, in percent, show the historical evolution of the global energy supply since the 1850s (Figure 3.5a). The first transition of the energy system started with the introduction of coal that replaced traditional sources such as fuel wood and working animals. This transition lasted about 70 years until the 1920s. During that time, the share of coal increased from 20 percent in 1850 to more than 60 percent by 1920. This development phase was characterized by the introduction of the age of steam, steal and railways. The next transition lasted another 70 years and is characterized by the replacement of coal by oil and natural gas. It can further be characterized by the rapid expansion of internal combustion, electricity, petrochemicals and the automobile. By the 1990s, more than 80 percent of global energy was supplied by hydrocarbon sources, that is, coal, oil and natural gas. Zero carbon sources such as hydropower and nuclear play only a limited role today, while traditional renewables supply the rest of the energy needs, especially in the developing countries.

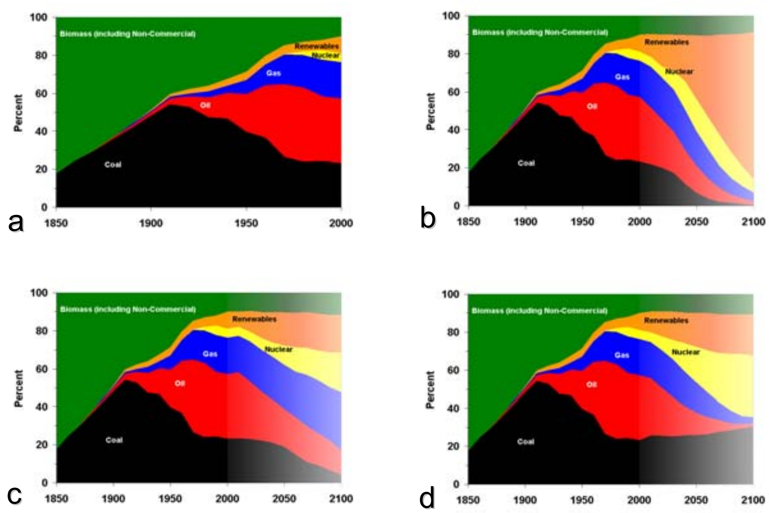


Figure 3.5: Historical evolution of energy systems structures, as shares of different primary energy sources (a) and future developments in SRES MESSAGE A1T (b), A1B (c) and A1FI (d) scenarios. Source: Based on Nakicenovic et al., 2000.

Looking into the future, different possibilities unfold across the SRES scenarios. Some of the scenarios, and in particular A1FI group shown in Figure 3.5, foresee a return to coal (Figure 3.5d). This is especially important for those regions of the world that have ample coal resources, e.g., India and China. Other scenarios put more emphasis on stronger reliance on oil and gas (Figure 3.5c), while yet other scenarios, and in particular A1T and B1, foresee a transition toward zero carbon sources with a much stronger role being played by nuclear, solar, modern biomass and other renewable energy sources (Figure 3.5b). The scenario shown in Figure 3.5b, in fact, would lead to a dominance of non-carbon energy sources by the end of the 21st century.

The alternative developments of the energy systems structures in the future across the scenarios imply developing a whole host of new energy technologies, and have different implications, for example, for energy infrastructure developments. In particular, Figure 3.5 has indicated a wide diversity of future energy systems structures, from a return to wider use of (clean) coal in A1FI and A2 scenario families to a transition toward a larger role of zero-carbon sources of energy (renewables and nuclear) in A1T and B1 scenario families. This large diversity across scenarios results in a wide range of carbon emissions. What is surprising however is that the structures of energy end use across all SRES scenarios are convergent. Figure 3.6 shows the shares of different final energy carriers across the scenarios.

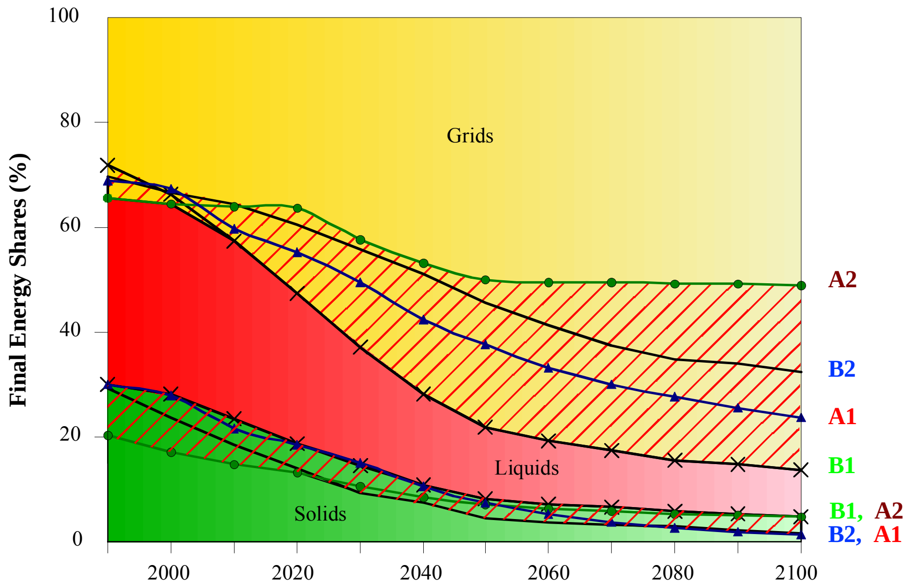


Figure 3.6: Global final energy shares (in percent) by form of delivery. Direct use of solids, direct use of liquids, and delivery of grids (gas, district heat, electricity, and hydrogen) for the four SRES marker scenarios. Overlapping shaded areas indicate variation across the four marker scenarios. Liquids includes oil products, methanol and ethanol. Solids includes coal and biomass. Source: Nakicenovic et al., 2000.

In 1990, solid, liquid and grid-oriented energy carriers share roughly a third of all final energy in the world. The share of the solids decreases in all scenarios. Basically, the direct use of coal and biomass disappears. This brings many environmental benefits at all scales, in particular reducing the in-door air pollution that is responsible for high rates of mortality in now developing parts of the world. All solid sources of primary energy are converted to (clean) liquids, electricity or energy gases. This is also the case in the coal-intensive A1FI scenarios and biomass intensive A1T and B1 scenarios. The share of liquids stays roughly constant across most of the scenarios but there is increasing role of synliquids produced from biomass, coal and in some cases also natural gas. The grid-oriented energy carriers become energy forms of choice increasing across the whole range of so diverse futures and energy systems structures in SRES scenarios. Initially, the shares of electricity and energy gases (primarily natural gas) increase but later syngases become also important. Especially the role of hydrogen increases in many scenarios and in particular in A1T and B1. These developments imply both large R&D efforts and vigorous diffusion of new energy technologies including hydricity systems. Infrastructure demands are large especially in scenario with large role of grid-oriented energy carriers.

The Post-SRES mitigation scenarios further amply these tendencies toward larger shares of hydricity technologies beyond 2050. These scenarios include measures and policies to achieve atmospheric stabilization of GHG concentrations in accordance with the Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992). Most of the mitigation effort is directed toward the reduction of carbon emissions well below current levels to some two GtC per year toward the end of the century. A large part of the decarbonization measures involves a shift away from hydrocarbon sources of energy or carbon capture and storage. In both cases, the share of electricity and hydrogen in final energy increases. Below, we will discuss how large is the role of hydrogen in across SRES and Post-SRES scenarios.

3.3. The Role of Hydricity Technologies

The potential emergence of a hydricity age has spurred increasing interest from both the scientific and policy community as of recently encompassing all the range from optimistic to skeptical views (e.g. Rifkin, 2002, NAE, 2004). Nonetheless, the available scenario literature has to date been extremely sparse[2] in sketching out possible diffusion scenarios of hydrogen technologies and associated investment requirements that could better guide technology R&D policies, especially under the additional "demand pull" of climate stabilization efforts.

In order to better understand the role of hydrogen in future energy systems across SRES baseline scenarios and Post-SRES stabilization scenarios, we consider here B1T and A1T-450 scenarios because they have the highest share of hydrogen and electricity in final energy. In part, this is because the high-level of investment in new energy technologies paves the way for emergence of hydricity age and in part because stabilization of atmospheric carbon emissions induces vigorous decarbonization. Both of these development lead to high shares of hydrogen and electricity. Figure 3.7 shows the growing shares of hydrogen and electricity in these two scenarios and also the declining importance of *embodied* hydrogen compared to *pure* hydrogen in final energy By embodiedhydrogen we refer to other energy carriers that either contain hydrogen such as other energy gases (e.g. methane) or other energy carriers produced from hydrogen such as a part of generated electricity.

Figure 3.7 shows that jointly hydricity forms of final energy are in the region of some 90 percent in both scenarios by the end of the century. The share of pure hydrogen increases from a few percent today to between 20 and 30 percent by the end of the century. The share of embodied hydrogen declines. Thus, there is a substitution of pure hydrogen for embodied hydrogen. In other words, energy gases remain to be an important energy form but their structure changes from natural gas to ever more pure hydrogen. Hydrogen and electricity are mutually exchangeable energy "currencies" (or forms) and this is reflected in the share of electricity generated from hydrogen (and vice versa not shown in Figure 3.7). Thus, the total amount of hydrogen in all forms, pure and embodied in other energy forms(including electricity) and the total amount of

[2] A notable exception is Barreto *et al.*, 2003. However also this most valuable study focuses on aggregate global trends in a single (optimistic) scenario and therefore does not offer technology specific scenario reviews for ASIA for a wider range of baseline and stabilization scenarios.

electricity are increasing vigorously.[3] This evolutionary development in the two hydricity-rich SRES and Post-SRES scenarios gives an illustrative roadmap toward the hydricity age.

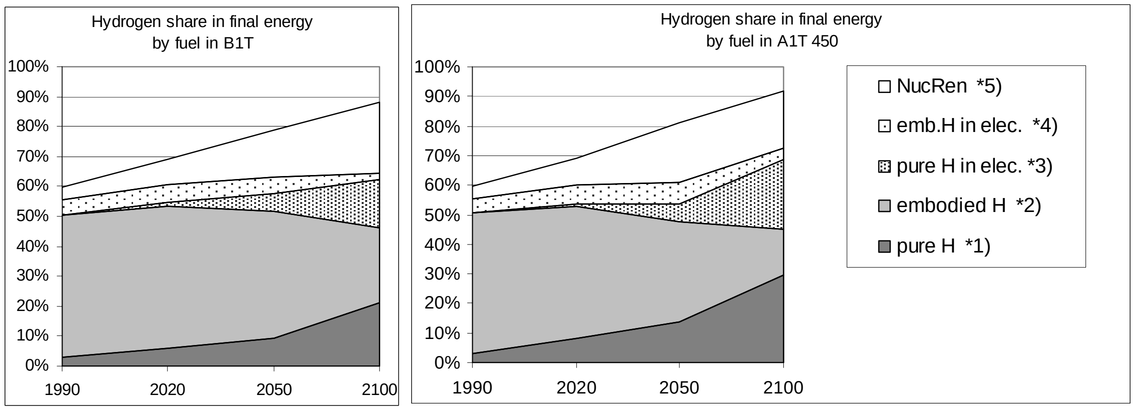


Figure 3.7: Share of hydrogen and electricity in final energy in A1T-450 and B1T scenarios. Hydrogen is divided into pure (elemental) hydrogen and embodied hydrogen (in other energy forms such as natural gas). The legend below explains the five categories of hydrogen and electricity in the figure.
**1) Hydrogen (H2) in final energy.*
**2) Hydrogen atoms embodied in fossil fuels and biomass in final energy.*
**3) Hydrogen (H2) consumed to produce electricity by fuel cells.*
**4) Hydrogen atoms embodied in fossil fuels and biomass to produce electricity.*
**5) Share of electricity from nuclear and renewables without carbon nor hydrogen.*

Table 3.2 summarizes the growing role of hydrogen across all SRES and Post-SRES scenarios. Today, hydrogen production worldwide is in the range of some 6 EJ or merely about 1.5 percent of total global energy requirements. Most of this hydrogen is used for non-energy purposes and is produced through steam-reforming from natural gas. Table 3.1 indicates the vigorous growth of the role of hydrogen across the scenarios throughout the century. Basically, hydrogen increases from ten-fold to hundred-fold during the century. A hundred-fold increase puts global hydrogen requirements 50 percent above the total primary energy requirements today! This is indeed a strong indication that the hydricity age does emerge in some of the scenarios – particularly in A1T and B1T.

Table 3.2. The role of hydrogen across SRES baseline scenarios and Post-SRES stabilization scenarios, in EJ per year.

		Range		
	1990	**2020**	**2050**	**2100**
Use of hydrogen, EJ per year				
Baseline	6	7.1 – 16.1	25.7 – 162.0	65.3 – 698.1
Stabilization	6	7.7 – 13.1	26.1 – 150.8	208.2 – 580.8

[3] This refers to total embodied and pure hydrogen in energy end use and implies for example that some of the embodied hydrogen reaches consumers as natural gas or electricity. However, this does not represent double counting of final energy but is rather intended to better indicate the growing importance of hydrogen in energy end use.

4. Hydricity Storylines

One of the hydricity storylines, simply called A1H&E, is primarily based on the A1 storyline with addition of strong emphasis on decarbonization as illustrated by the A1T-450 and 550 scenarios, two mitigation variants of A1T subgroup that leads to stabilization of atmospheric concentrations at between 450 and 550 ppmv (compared to 280 ppmv pre-industrial levels about the 1800s and current levels of some 380 ppm) toward the 2150s. An important characteristic adopted in the A1H&E storyline is the rapidly growing need for energy services especially across highly urbanized world beyond 2050. In conjunction with rapid decarbonization, this leads to development of extensive and massive energy (and other) infrastructures and most importantly for the hydricity age, the widespread diffusion of carbon-free, grid-oriented energy carriers, electricity and hydrogen, and of centralized conversion systems. As was shown, the A1T-550 scenarios already includes very rapid deployment of hydrogen as an important future energy carrier. The main difference is that in A1H&E hydricity forms become the energy carriers of choice.

The other hydricity storyline, simply called B1H&E, is based on the environmentally oriented B1 scenario family that achieves most of the criteria associated with the sustainability transition. This sustainable world is primarily renewable with high, but not excessive growth rates. It is also a very equitable world with a high and universal decarbonization of energy. This also promotes hydricity technologies. However, many of the systems are generally more decentralized and community oriented. The storyline does not necessarily imply the development of global and perhaps not even continental scale infrastructures. Energy systems are interconnected but not highly integrated. The emphasis is on local (on-site) conversion and end use. The role of hydricity technologies is large and associated with vigorous growth also in this storyline. The difference is that both electricity and hydrogen are produced more in a decentralized fashion and used more locally. As was also shown, the B1T scenario on which the B1H&E storyline I based already includes very rapid deployment of hydrogen and an important energy carrier. As in the case of A1H&E, the main difference is that in B1H&E hydricity forms become the energy carriers of choice.

Table 4.1. Major Characteristics of the Two Storylines.

	A1H&E	B1H&E
Description	"High Growth", "Technopolis", "Rich & Clean", "Unlimited Skies", "Affluent", "Centralized", "Business Class"	"Sustainable", "Technogarden", "Green & Clean", "Down to Earth", "Equitable", "Decentralized", "Chat Room"
World view	Technology-intensive hydricity scenario Rapid technological progress Globalization of economy and lifestyles Convergence among regions and relative development catch up. Market-based solutions, strong institutions, liberal government regulations and high investments	Green and sustainable hydricity scenario Global solutions toward social equity and environmental sustainability Harmonization in social and environmental policies, but diversity in culture Strong government regulation supported by high environmental consciousness Decentralized and decarbonized world
Population	Low growth, with its peak at 9 billion around 2050, and 7 billion in 2100 [*1] Population over age 60: 40% in 2100 [*2]	Low growth, with its peak at 9 billion around 2050, and 7 billion in 2100 [*1] Population over age 60: 40% in 2100 [*2]
Demographics	Household size shrink very much, from 4.2 in 1990 to 2.3 in 2100 [*2] High growth of households, from 1.3 billion in 1990 to 2.7 billion in 2100 [*2]	Household size shrink not so much, from 4.2 in 1990 to around 3 in 2100 [*3] Smaller growth of households, from 1.3 billion in 1990 to 2.0 billion in 2100 [*3]
Economy	Very high economic growth, around 3% per annum [*1] Quantity above sustainability but with high efficiency and low emissions	High economic growth, around 2.5% per annum [*1] Durable goods and quality are valued Dematerialization and virtual consumption
Urbanization and housing	Highly urbanized, high-density megacities with mass transit, low-density, automobile-dominant cities Housing size large with high per capita floor area Growing number of families are single person households Insulation, seasonal storage	Compact cities and suburban sprawl with highly-developed public transportation systems Housing size smaller, more compact People tend to live multiperson households Excellent insulation, seasonal storage, compactly build houses, cars part of house energy system
Transport	Very high demand for passenger mobility and freight transport Around 4 billion vehicles [*4] Private transportation dominates in rural areas, mass transit in megacites. High demand for long-distance and inter-continental travel: maglevs + hypersonic.	High demand for passenger mobility and freight transport Around 3 billion vehicles [*4] Public transportation popular and private is also coordinated publicly (like taxis) Cities are connected with rapid train systems and efficient aircarft

Table 4.1. Continued

Energy supply	Large-scale renewables including off-shore farms, nuclear including HTR, carbon capture and storage	Distributed renewable systems with on-site generation, decentralized systems with grid connection but without large-scale transport
Energy transmission	Integrated infrastructures including the supergrid for hydricity transport	Local and regional grids for electricity, liquids and gases
Residential end-use	Nanomachines and robots Convergence of information, cognitive and communication technologies Energy cascades and cogeneration	Local generation with emphasis on low-energy intensity lifestyles Integrated cogeneration and transport through fuel-cell vehicles connected to buildings
Industrial end-use	Efficiency improvement rate very high Industrial ecology closes the materials flows.	Efficiency improvement rate high and change toward eco-production Dematerialization and production with zero waste
Carbon sequestration	Large scale sequestration, more than 250 GtC from 2000 to 2100 [*5] Sequestration into depleted fields, aquifers and deep ocean Well-developed infrastructure for carbon transportation on continental scales	Moderate scale sequestration, 50 to 100 GtC from 2000 to 2100 [*5] Local storage in depleted fields. Infrastructure for carbon transportation not developed. Carbon is transported only to depleted gas and oil fields.
Agriculture and biomass	Rapid growth of agricultural productivity Landless agriculture (industrial production in closed "greenhouses") Virtual independence from natural ecosystems for food services Increasingly meat diet	Sustainable agriculture with low intensity of energy and fertilizers, ecologically sound Inefficient animal production on land decreasing Aqua-cultivation Increasingly vegetarian diet
Technology	Convergence of emerging technologies into a new techno-economic paradigm: Nanotechnology, biogenetic technology, information, cognitive and information technologies. Large-scale systems and integrated infrastructures High-levels of R&D and initial technology support.	Smaller-scale, local systems. High emphasis on dematerialization, efficiency and low waste On site systems with virtual integration (rather than physical). High-levels of R&D for eco-sustainability and low emissions. Emphasis on local solutions.

[*1] Nakicenovic *et al.*, 2000, SRES
[*2] O'Neill *et al.* 2001. Population and Climate Change.
[*3] based on an assumption that education and policies encourage larger households.
[*4] Schafer and Victor (1999) estimate that absolute levels of mobility in 2050 around 100 trillion passenger-km, and its 40% from car travel. Based on Schafer and Victor (1999), Turton and Barreto (2004) estimate about 37 trillion km car travel in 2100. Assuming the 1 hour/day travel-time budget and average speed at 50km/hour, these figures mean that the number of future vehicles would be around 2 billion, either in 2050 or in 2100.
[*5] TAR: 250 Gt-C for A1T-450, 200Gt-C for B1-450, and 50 Gt-C for B1-550.

5. A1H&E Storyline

The A1H&E storyline describes a world that is characterized by rapid demographic transition (declining mortality and fertility rates) and hence low population levels, very high productivity and economic growth in all regions, and comparatively high energy and material demands.[4] The rapid and successful economic development worldwide is driven by high human capital (education), innovation, technology diffusion, and free trade. These are the main sources of productivity growth and modernization of social and economic structures, largely following the "Western" (e.g., OECD) model.

These developments in the A1 scenario family and the underlying storyline are rooted in the successful globalization in the world that results in very high productivity rates while preserving local identity and diversity. In this storyline, institutions are effective, markets are functioning well, property rights are universally respected and poverty basically eradicated, as we know it today. The main motor of this unprecedented affluence in the world is development in all of its facets. Many of the now poor regions and social strata in the world achieve a conditional (and relative) catch-up. They leapfrog some of the development stages even though they do not generally manage to close the income or consumption gap in absolute terms. This means that all parts of the world would achieve high levels of affluence by the end of the 21st century, even if disparities will not have disappeared entirely. In any cases, the current distinction between "developed" and "developing" countries in any case will no longer be appropriate in this scenario. At the same time, now affluent regions of the world generally become even more affluent. Markets rule. Geopolitically, this world could be described as "Pax-Americana", a world of hegemony associated with one single world power, but a world where this stable political, economic and social order furthers growth and development to benefit of many.

There are many possible symbolic "images" of this storyline that can be captured by catch-phrases like: "Fly High", "Technopolis", "Rich & Clean" or "Bussines Class" world. An earlier catch phrase for this storyline was the "Tiger World" to denote rapid technological, institutional and economic catch-up of the so-called four Tigers in Asia during the 1990s. They portrayed the successful development paradigm associated with the A1H&E storyline. The color image of this storyline might be silver, chrome or titanium.

5.1. A1H&E Characteristics

The principal scenario drivers are *prosperity and affluence*. All major scenario-driving forces are closely linked to prosperity levels, with actual causality links going both ways. For instance, demographic variables co-evolve with prosperity: mortality declines (life expectancy increases) as a function of higher incomes enabling better diets and affordable medical treatment. In turn, changes in social values and relations underlying the fertility transition along the historical European and Asian experience pave the way

[4] The A1H&E storyline is rooted in the SRES A1 scenario storyline (Nakicenovic *et al*., 2000). The emphasis on hydrogen and electricity and the broader narratives presented in this section (5.) are based on an earlier draft of the A1 storyline and quantification by Arnulf Grübler that dates back to 1998. It has been updated in the meantime to reflect some of the recent developments and scenario literature. We reproduce parts of this storyline here *verbatim* and use it extensively to develop the hydricity story. We are grateful for the explicit permission of the author to use this material in this report (Grübler, 2005a).

also for wider access to education, modernization of economic structures, market orientation, etc. that are a key for innovation and diffusion of best practice technologies underlying the high productivity, and hence economic growth of the scenario. To summarize: High prosperity levels allow significant increases in investments into education, R&D, and the experimentation with new product and process innovations that in turn nurture high demand and productivity growth and hence, exert a powerful positive feedback mechanism on economic growth.

A corollary of the high economic growth via innovation and free trade logic of the scenario is that the mobility of people, ideas, and technologies co-evolves closely with the high economic growth rates of the scenario. Traditional, as well as novel (supersonic, maglev's) transportation modes co-evolve with radical changes in ICT (virtual Internet, robotics and nanotechnologies). Transport and communication are not only complementary in this scenario but enhance each other synergistically. Energy technologies embrace a wide portfolio of hydricity systems (supergrid, CO_2-turbines and other zero-emissions power plants, high-temperature reactors, large-scale photovoltaics systems, off-shore and other remote wind farms as well as pervasive use of fuel cells). There is a strong "convergence" across all of these technologies to produce a new techno-economic paradigm, growth and the resulting affluence and prosperity in the world.

Limiting Factors and Diseconomies

The core bifurcation of the scenario with respect to hydricity technologies unfolds around alternative paths of addressing externalities of massive growth in energy services required to sustain mobility, communication and information flows worldwide and in general high levels of material and "dematerialized" consumption patterns. These externalities include in particular congestion and local and regional environmental protection in case of transport, issues of privacy and informational security in case of communication, and issues of waste management and ecosystem protection in case of material consumption.

One aspect of this storyline, let us call it the "Unlimited Consumption" (or "Growth to Limits"), necessitates to mitigation of numerous negative externalities through market forces that promote vigorous technological innovation efforts, reviving the high experimentation rates and short innovation product life cycles, characteristic of the early pioneering days of air transportation and mobile telephones. Vigorous innovation is therefore the industry response for overcoming potential barriers arising from the formidably high growth of energy services in this storyline. Safety, privacy, congestion, and local and regional environmental impacts (noise, emissions) are addressed successfully by introduction of advanced technology concepts. The motivation for these innovations are less environmental, but simply an economic innovation response to overcome bottlenecks, to avoid stringent regulation by the public sector, and to allow for sustained growth. In this scenario, anthropogenic interference with Earth systems such as the adverse impacts on biosphere and ecosphere turn out to much lower than previously anticipated and the high income societies of the future can easily adapt to it (either through substitution of ecosystems services through technology such as bioengineering or through management of threatened ecosystems). In any case, global environmental issues are relatively high on the priority list in this storyline. However, they do not result in massive behavioral change. Instead, the measures to counter the adverse environmental impacts are primarily directed at closing the "production and consumption cycles" such as the decarbonization of energy carriers (thus hydricity technologies) and central conversion facilities. One could say that the natural ecology is replaced by industrial ecology in this storyline there where people live in high densities. Elsewhere, land is "returned" to nature. This is consistent with recent developments in Europe and North America where human land-use has declined in favor of (mostly managed) nature.

Regulatory Frameworks and Globalization

Many of these tendencies in the storyline lead to strong regulatory frameworks. Strict governmental regulations (including the global level) provide for a regulatory "push and pull" on technology: "Pulling-in" desirable technologies and characteristics via regulation and incentives; "Pushing-out" undesirable ones. Initially, regulatory push and pull factors focus on rapid, incremental improvements of existing technologies (e.g. fuel-efficient prime movers such as aircraft engines), but over the longer-term increasingly the focus shifts to radical technological solutions, e.g. banning progressively the use of kerosene in air transport in order to stimulate the market adoption of cryogenic hydrogen aircraft. Overall, this does tend to result in less "diverse" technological change and experimentation in this storyline compared to a hypothetical scenario variant with less regulatory interference. The advantage is that the direction of technological change is to rapidly respond to evolving environmental concerns, especially climate change, whose impacts turn out to be much larger than previously anticipated, unfolding rapidly already in the first decades of the 21st century. This leads to a frenzy regulatory effort of emission reduction and impact mitigation, while still maintaining the high economic growth priorities characteristic of this scenario family.

As a consequence of these general tendencies, A1H&E storyline specifies more emphasis on the centralized energy conversion, distribution and end-use patterns. It is an urbanized world but as mentioned with much of the land "given back" to the nature. Humanity is concentrated predominantly in large urban corridors and mega-settlement patterns. Current examples would be the Tokyo-Osaka corridor, the Ruhr cluster in Europe, the eastern seaboard in the US and many of the main mega-cities in the developing parts of the world ranging from Delhi, Beijing and Mexico City to Sao Paolo. Such settlement patterns could emerge in the future across the Trans-Siberian Corridor and elsewhere in Asia, Africa and Latin America. They may become more focused in the "North" today but are not all that likely to expand massively due to the aging and declining population trends. A1H&E storyline implies massive infrastructural developments in particular in the now developing parts of the world. In the energy area this implies development of large sources of primary energy, integrated (super)grids from electricity and pipelines to cryogenic networks for energy gases. Most of the conversion and transformation would be central providing very flexible and environmentally benign structures of energy end use. Lifestyles are likely to change fundamentally in this future world as time progresses, especially toward the end of the century, but this version of the hydricity age story is in principle consistent with current lifestyles and settlement patterns of the most affluent parts of the world.

5.2. A1H&E: Key Drivers

Population, economic development, and regional disparities

The linkage between demographic and economic variables in A1H&E storyline is based on present empirical observations: The affluent live long, they have few children and live in small (often single-person) households. High per capita incomes are thus associated today with both low mortality and low fertility rates. Advanced and widespread medical technologies avert emergence of pandemics and other "premature" causes of death.

Causality links are bi-directional. For instance, increasing economic affluence and higher workforce participation of women may lower fertility rates. Alternatively, high education and resulting female empowerment result in modernization of traditional social structures, lowering fertility rates, and subsequently provide the social conditions for a "take-off" in accelerated economic development.

Combining low fertility and low mortality results in a rather low population projection, characterized in addition by an considerably "graying" of the population age structure. The SRES A1T scenario suggests a quantification in which fertility rates could range between 1.3 to 1.7 children per women, replicating current sub-replacement fertility patterns of the affluent globally. Mortality rates would also be very low, with life expectancy approaching 100 years on average. In this scenario global population would peak below 9 billion by ca. 2050, in order to decline thereafter to some 7 billion by the end of the 21st century.

The economic growth scenario takes analogy to historical examples of most successful economic catch up, such as Scandinavia and Japan after WW II, to describe possible future development patterns of current low-income countries. The scenario is one of conditional convergence in which "the poor get richer, and the rich slow down".

The global economy in the A1H&E storyline expands at an average annual rate of three percent per year to 2100, i.e. at the same rate as the average of the successful OECD countries since mid-19th century. Non-Annex-I[5] economies expand with an average annual growth rate of four percent per year twice as fast as Annex-I economies. Over time, growth rates decline as per capita incomes increasingly approach current OECD levels. Based on the quantification of the SRES A1T scenario the global economy could roughly triple each by 2020, 2050, and 2100; approaching 50, 150, and 500 trillion $ over these three time periods.

Equity is not a major concern in the scenario, but rather a "byproduct" of the high rates of economic development. Existing per capita income gaps between regions close up in relative terms from a factor of 16 (6 in purchasing power parity terms) between Annex I and Non-Annex I countries in 1990 down to a factor of about two in 2100 (in a similar way as income gap "closed" of Western Europe and Japan to the US in the 20th century). Approximately by 2030 Non-Annex-I GDP would surpass that of Annex-I economies. Per capita income level disparities are also reduced, but differences between regions are not entirely eliminated. Non-Annex-I per capita income could reach the

[5] As defined in the UNFCCC (1992). Annex-I countries correspond to the industrialized countries, subject to the provisions of the UN FCCC. Non-Annex-I countries correspond to the developing countries.

1990 Annex-I level (of some $14,000 per capita) by ca. 2040/2050. By 2100 per capita incomes would approach $100,000 per capita in Annex-I countries, and could reach up to $70,000 per capita in Non-Annex-I countries, making current distinctions between "poor" and "rich" obsolete.

Box: Demographic and Economic Development in ASIA Region

The global demographic and economic tendencies in the A1H&E storyline are reflected n the regional development patterns. For example, population growth in ASIA would stabilize at a level of about 4.2 billion by 2050 in order to decline thereafter under the high-income, below-replacement fertility assumptions characteristic for this scenario storyline. By 2100, ASIA's population would decline to a level of close to 3 billion inhabitants, characterized by high income and resource consumption levels. Per capita income levels could reach $75,000 by 2100 in this (extreme) high growth storyline and primary energy use in ASIA could reach some 860 EJ by 2100, i.e. twice the level of current *global* energy use. Clearly, the infrastructural and technological implications of such development are unprecedented at this scale. This is one of the reasons why large-scale and integrated energy infrastructures are an important feature of the storyline.

Social Trends and Governance

The economic growth and conditional convergence focus of the "High Growth" scenario go hand in hand with an increasing convergence of social values and lifestyles along the "Western" hedonistic model, furthering emphasis on small family size, material well-being, and leisure. Increasing consumerism of the developing world is thus a central feature of this kind of scenario. *Ceteris paribus*, material demands would be similar to those of the affluent OECD countries at similar levels of per capita income, even if regional and cultural differences will not entirely disappear. Asians, for instance would continue "to eat rice" and still appreciate more collective leisure experiences in traveling together in groups and for shorter time periods, whereas Americans would ultimately adopt healthy Mediterranean diets and Western European recreational travel models of long summer vacations to coastal areas combined with more individualistic extensive "adventure" travel to far away destinations (even if those no longer would be "exotic" in the traditional, 20th century sense). Nonetheless, traditional consumerism might not grow linearly with affluence indefinitely. As evidenced in food habits and expenditures, saturation phenomena might set in, furthering rather qualitative than quantitative growth, e.g. in high quality services, arts, and special, high value leisure activities. Thus, affluent consumers, instead of taking more single long-distance, low-budget trips would increasingly opt for fewer, but extreme high luxury "cruises" in which trips *per se* are more important than the destinations visited, combining sequences of "world around" interesting destinations much along the lines of current luxury ocean cruises. Thus, even with fewer trips, travel distances (and thus air travel demand, expressed in passenger-km) might continue to grow. With rising incomes, travel budgets would rise accordingly, approaching globally some 15 percent of available income, as is the case today in the most affluent societies, split however over a variety of different transport modes, with local and regional transport continuing to take the lion's share. However, ultimately travel time budget constraints (on average one hour per day spent traveling) might become dominant even in air transportation resulting in a revival of super- and hypersonic aircraft designs, including orbital flights.

Such developments would unfold first for the most affluent and powerful, e.g. in form of super-sonic executive jets, but would gradually become widely available also for the "everyday" consumer (e.g. post 2050) in form of family jets or scaled-up, spacious super- and hypersonic aircraft designs for hundreds of passengers. Consumers in such a scenario would therefore vigorously refuse current aircraft designs, combining slow subsonic speed with dense passenger "packing". Beyond 2070, even space travel might emerge as a small, extremely high value market niche. Both supersonic and hypersonic flight as well as space travel would be based on hydrogen propulsion. Thus, hydrogen would appear to be a necessary technology in the A1H&E storyline.

Overall, the economic focus of the scenario presumes both "laissez-faire" as well as effective governance at the regional and international level. (The traditional small nation state would largely be gone, replaced instead by regional economic associations and trans-national companies.) Non-interventionist governance is the key concept for not intervening with the functioning of free markets, innovation experimentation, and economic growth. Governance would instead focus on a few key areas of public goods and externalities, such as knowledge (education and R&D), market failures (technological standards in order to reduce high costs of parallel standards and assuring market transparency), as well as environmental externalities.

Varying degrees of government intervention (regulation) provides for the core bifurcation into two sub-scenarios.

One subgroup might be related more to the original A1T story that is not limited by climate considerations. There, hydricity emerges because of convenience and other driving forcers rather than the climate protection *per se*. In **"**Unlimited Skies**"** versions of the A1H&E storylines, governments serve primarily as "moderators" to raise awareness to industry and act as facilitators in R&D and technology development consortia. The traditional regulatory paradigm is replaced by "soft" (talk to) policy concepts, providing for few stringent regulatory constraints.

Conversely, in "Regulatory Push&Pull" or "Stabilization at 450ppm" versions, industry recognizes the advantages of predictable regulatory environments and relies on regional and international institutions to provide equal level playing fields and common environmental standards for all market participants. Increasing attention for instance is devoted to preserve local air and water quality, that trigger both conservation innovations as well as novel, zero-emission technologies, particularly in the transport sector. A new hydrogen infrastructure develops first incrementally along with natural gas pipeline systems to provide energy for fuel cell vehicles in megacities. First dedicated pipelines emerge by 2040, by which time also some aircraft and automobiles start use hydrogen fuel. Effective governance is especially called for in addressing climate change, especially after its effects assume dramatic proportions in the near-collapse of the North Atlantic thermohaline circulation and the Asian Monsoon between 2052-2058. An ambitious target of a zero-carbon global economy by 2100 is agreed by 2060, and great structural shifts begin to take place after 2075 and yield substantial emission reductions by 2100, even if it takes yet another 40 years to fully phase out carbon emissions. In such a scenario zero-carbon energy sources could account for up to 85 percent of global energy supply by 2100.

Environment and Ecology

By assumption (and cultural Western development model bias) the ecological resilience in the scenario is assumed to be high. Ecological concerns are also low in their own right. Instead the valuation of environmental amenities is strictly valued in monetary terms, with the valuation closely linked to rising income levels. Non-congestion, clean water and air, avoidance of nuisance by traffic noise, recreational possibilities in nature, etc. all assume increasing importance with rising affluence, albeit preferences for environmental amenities may remain different across regions and income levels. For instance urban air quality and human health would be valued highly even at income levels lower than those prevailing in England where stringent air quality measures were introduced after the “killer smog” of 1952. Reduced particulate and sulfur air pollution are assumed to become a matter of major consumer preference at levels of $2,000 to 3,000 per capita income in Asia. Altogether, the concept of environmental quality might change in this scenario from “conservation” of nature to active “management” (and marketing) of natural and environmental amenities and services. Because environmental quality can be marketed for products and services, there is little need for government regulation *per se*, as polluting producers and products are essentially driven out of the market. “Life cycle semiconductors” are attached to any product/service sold recording and communicating all externalities associated and providing complete market transparence. Product responsibility is also valued high, litigation and compensation for externalities imposed are the norm in this affluent world. For instance, already by 2020, compensation schemes ($1000 per capita for each exposure to above 75 dB) are established by court ruling in the US to compensate for aircraft noise, a trend that spreads also to Europe and Asia, especially in high density urban corridors by 2050. Similar market-oriented regulatory frameworks can be imagined for other spheres of human activities in this storyline

In a sub-scenario variant, above “free market” philosophy for the environment is contrasted by a strict regulatory approach. Instead allowing for market compensation of environmental damages, environmental externalities are aimed to be “regulated away” altogether, especially after it became apparent that the scale of climate change damages would exceed any reasonable financial compensation even in a $150 Trillion GDP world economy of 2050. This “Regulatory Push&Pull” scenario would gradually branch out from the “High Growth” world after 2020, including first local and regional environmental issues, and after 2060 also a strict global climate change regulatory regime.

Resources and Technology

Resource availability and technology are tightly interrelated in this High Growth, “high tech” storyline. High productivity growth results from substantial technological innovation and both contribute to economic growth, expansion of accessible resources, and improved efficiency in resource use. Resource availability is largely technology driven, rather than the other way around. For instance, new non-fossil technologies like hydrogen emerge out from supply push factors related to technological innovations in fuel cell vehicles rather than being “forced” by increasing resource scarcity. As a result the call on fossil resources, which is comparatively high in this High Growth world, is mitigated by continuous innovation and structural change. For instance, by 2020 zero-carbon energy sources could contribute some 15 percent of global energy, a share that would expand to roughly one third by 2050, perhaps approaching two thirds by 2100 (as illustrated in the comparable IPCC-SRES-A1T scenario).

In domains of significance for environmental regulation in the **“**Regulatory Push&Pull**”** sub-story, this progress would even be faster: reaching some 20 percent global market share by 2020, 40 forty by 2050, even 85 percent by 2100 (as illustrated in the A1T scenario).

Box: Nanotechnology

Nanotechnology in conjunction with advanced information, communication and energy systems holds the promise of improving performance and reducing materials and energy requirements. The basic idea already possible in the laboratory is to make machines such as motors, robot arms or computers much smaller than a living cell on the scale of a nanometer, thus the name nanotechnology. Possible applications are widespread, from communications, medicine, transportation to agriculture and for industry in general.

Nanomachines would lead to unprecedented dematerialization along with much lower environmental impacts on all scales including much lower demand for energy. There are however also many inherent dangers. Nanomachines like bacteria are tiny. Somehow, they would need to self-replicate and self-repair themselves. There is also an inherent implication of self-organization. Today, experimental nanomachines are powered by radiant energy (eg. microwave) or batteries but if they ever become truly autonomous they would need to store energy in between “charge” times. Hydrogen and electricity offer in combination with each other two ideal, non-polluting energy carriers for the nano-world.

Nanotechnologies could become an essential component of the new techno-economic paradigm through convergence of many technologies into fundamentally new systems or they may remain to be very specialized diffusion only in some narrow niches. Consider a hypothetical case of bacteria-scale robots that could be administered for both diagnostic and repair duties in human bodies but also in many other devices and living beings. This would require billions if not trillions of such nano-robotic devices. The diffusion would indeed be very pervasive. The other possibility is that such machines are used only for medical purposes under very controlled conditions (say only in hospitals). In that case, the diffusion would be rather limited and not all that different from the scale of MRI machines used today for medical purposes.

Overall, the dynamism of technological innovation is broad-based, including many radical solutions, from “engineered” human health, landless farming, bio-engineered renewable feedstock and structural materials. High rates of experimentation and a free market orientation provide evidently for numerous negative surprises, which are however addressed by compensatory and adaptive mechanisms rather than by traditional regulatory banning regimes. The latter option would however be considered for key strategic areas such as climate change, assumed to be significant in the “Regulatory Push&Pull” sub-scenario.

Communication and Transport

Communication and transportation technologies and styles are highly homogeneous and extremely developed in this "High Growth" world, extending current virtual and physical communication patterns of urban elites to a global phenomenon, driven by the twin driving forces of income growth, and continuous cost reductions, particularly in communication technology. Information and data transmissions finally really become "too cheap to meter" and as of 2020 communication costs for all modes drop to zero globally. One hand side this new economic balance shifts emphasis from physical, "batch" travel to instantaneous mobility, especially after virtual realty avatars and sensuality robots available for transmitting a wide range of sensual experiences (vision, sound, smell, texture) become widely available after 2040. On the other hand, vastly increased communication flows also induce additional travel. The end result might simply be "dynamics as usual" from a long-run historical perspective, where communication and transport flows have roughly grown at two percentage points faster than GDP (translating to a 5 percent annual growth rate globally for the average three percent per year GDP assumed for the "High Growth" story).

Box: Decarbonization in the Hydricity Age without "Tears"

Natural gas is likely to be a bridge toward a hydrogen future. Even though methane has roughly half the carbon emissions compared to coal, large-scale use of natural gas by future societies, in conjunction with climate protection, may require widespread decarbonization. This is for example necessary in Post-SRES A1T-550 stabilization scenario. Marchetti (1985) has proposed an effective way of achieving this goal. Essentially, natural gas would be steam-reformed into hydrogen and carbon dioxide close to the wells. Carbon would be reinjected in the reservoirs to achieve enhanced recovery or into the aquifers in the vicinity of the facilities. This is similar to the Sleipner Project in the North Sea where carbon dioxide is separated from methane and reinjected into an aquifer below the sea and below the reservoir.

Separated hydrogen would either be transported by its own infrastructures in pipelines or as a super-cooled liquid or it could be blended to the methane and separated again through membranes for use in smaller-scale facilities. The larger ones could use the mixture of methane and hydrogen in conjunction with carbon capture. A possible technology could be zero-emissions power plants that utilize carbon dioxide as a working fluid in the (high-pressure) gas turbines. These could use an oxifuel mixture of methane and hydrogen that would result in water vapor and additional carbon dioxide after combustion. Water vapor could be separated, additional carbon dioxide stored and the rest recycled back into the turbine.

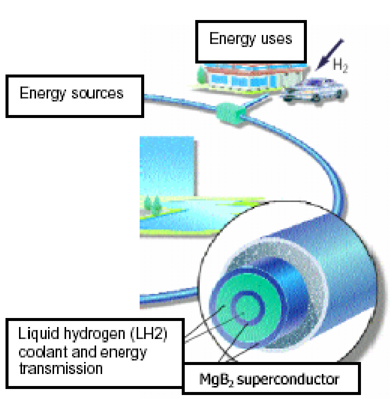
Steam reforming of methane requires energy because it is an endothermic process. About half of the energy is stored in the form of hydrogen and about half is required for the reaction. This can be provided by a zero-carbon source such as high-temperature solar or nuclear power (HTR). The decided advantage of this scheme is that methane essentially becomes the feedstock for production of hydrogen substantially reducing the carbon dioxide storage requirements and natural gas use.

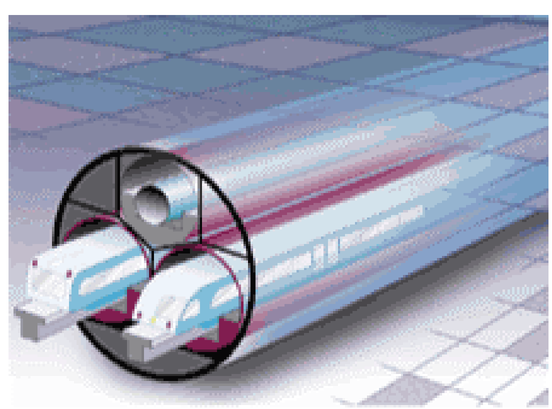
Rather than a "global village" future this is however rather one of "global cities" because existing trends towards even higher urbanization continue in this scenario as cities provide the highest "network externalities" for the educational and R&D intensive economic development pattern underlying the scenario. Regional differences in settlement patterns however persist ranging from fragmented "compact" (but large, i.e. 20+ million inhabitants) cities that draw on (and depopulate) their respective rural hinterlands in Latin America (e.g. Sao Paulo) to urban "corridors" connected by high capacity communication and transport networks in Asia, Europe and in the coastal areas of North Africa and North America. Regional transport networks include high speed trains, maglev's, ultimately fusing short- and long-distance transport technologies (metro's) into single interconnected infrastructures making current distinctions between short- and long-distance travel increasingly blurred. Air transportation would focus on intercontinental travel and some feeder functions to smaller urban areas, but is unlikely to provide for the vast amounts of passenger flows traveling *within* the regional urban clusters as daily commuters. Ultimately, ballistic intercontinental travel might become a reality in this storyline.

Box: Energy SuperGrid for the Hydricity Age

The Energy SuperGrid proposal calls for supplementing the existing high voltage electric grid using superconducting dc cables for power transmission with liquid hydrogen used as the core coolant. The electric power and hydrogen would be supplied from nuclear and other source power plants spaced along the grid. Electricity would exit the system at various taps, connecting into the existing ac power grid directly in the urban load centers. The hydrogen would also exit the grid, providing a readily available, alternative fuel, for perhaps fuel-cell based automobiles. Hydrogen could also be generated locally by electrolysis using the electricity supplied by the superconducting cables.

The need for the superconducting cables arises because of the current stress on the existing ac transmission grid. In most urban areas there is little spare transmission capacity and few available right-of-ways for the construction of new lines. Replacing the petroleum-based transportation energy worldwide, an amount equal to about a third of all final energy, with hydrogen will require either new hydrogen pipelines or large amounts of electric energy to generate the hydrogen locally. The SuperGrid proposal addresses both issues through its subterranean electric/hydrogen "energy pipeline."





In short the Energy SuperGrid is a proposal for an enhanced infrastructure to meet the energy needs of large urban areas of future megacities if one assumes a drastic reduction in fossil fuel consumption, particularly petroleum and perhaps natural gas.

The Energy SuperGrid concept goes beyond the vision of a future hydrogen economy, or the simple extrapolation of electrification, to a duality of a hydrogen – electricity future, *hydricity*. In this vision electricity and hydrogen become synergistic elements in the future energy infrastructure. This energy delivery grid interconnects remote sources with load centers, links regional ac interconnections and connects concentrated population centers with remote nuclear and modern renewable resources and integrates hydrogen utilization in combined heat and power facilities and hydrogen storage for mobility or transportation usage.

Separable from the Energy SuperGrid, but a possible valuable dual use, would be the eventual common use of the energy pipeline tunnels with underground high-speed transportation system using maglev propulsion. A common tunnel for energy and transportation is a speculative concept if a combustible fuel is transported in the common tunnel (see the illustration above). For electricity and transportation systems it is technically feasible and well founded today.

The overall Energy SuperGrid R&D program needs to pursue several technological platforms in parallel along with a systems engineering-economics effort that integrates and cuts across the technology platforms. Following the practical demonstration of engineering feasibility, at what for this concept might be considered a pilot scale, a series of real world, field experiments should be pursued with physical distances of first kilometers and then tens of kilometers.

The large urban agglomerates and the high transport demands of a high material growth economy generate potentially vast congestion constraints, solved by applying either market based instruments (prices) as in “Unlimited Skies” or by governmental regulation as in “Regulatory Push&Pull”. Market based instruments would include for instance systematic “just-in-time” access and parking fees, auctioning of (the limited number) of new car and truck registrations in megacities, etc. much along the (stringent) Singapore model. Therefore even at very high income levels, car ownership rates could be comparatively low, and in extremely densely populated areas rather a luxury than a means of mass-transport (cf. Hong Kong). In lower density areas car densities are high (more than one car per inhabitant); their fuel systems oil versus electricity or hydrogen being varied regionally. Furthermore, intercontinental transport could well be provided by (energy and GHG intensive) hypersonic aircraft fueled by methane or hydrogen. Hypersonic transport would be the physical transport equivalent of the high capacity virtual communication “backbones” of a truly global economy, paving the way for space travel that could emerge towards the end of the 21st century (post 2070).

Development and integration of global grids and networks is an important paradigm of the A1H&T storyline. This is best illustrated by the vision of a continental supergrid that delivers electricity and hydrogen in an integrated energy pipeline (see the box above). The notion of a global SuperGrid was pioneered by Chauncey Starr (Overbye *et al.*, 2002) of the Electric Power Institute (EPRI). The supergrid would use a high-capacity, super-conducting power-transmission cable cooled with liquid hydrogen produced by advanced nuclear plants, with some hydrogen ultimately used in fuel cell vehicles and generators. A most radical version of this global infrastructure would include maglev's and high-capacity communication and information networks within the same infrastructures. This way energy, mobility and information would connect and integrate the globe into one anthropogenic system.

6. B1H&E Storyline

Like A1H&E, the B1H&E storyline also describes a world that is characterized by rapid demographic transition (declining mortality and fertility rates) and hence low population levels, productivity increases directed at environmental sustainability in all regions, combined with very high energy efficiencies, low materials demands and fundamental lifestyle changes.[6] The transition toward the sustainable development worldwide is driven by high and universal environmental awareness. This is reflected in high human capital (education), innovation, technology diffusion, and international frameworks for environmental and ecosystems protection. These are the main sources of change in social and economic structures toward sustainability on all scales from local to global, largely following the "green" ideals and "dematerialized" lifestyles.

These developments in the B1H&E storyline are rooted in the successful globalization in the world toward environmental protection and sustainability. This transition is directed at preserving local identity and diversity but within the context of harmony with nature. Ecosystems services are an essential and ever more important aspect of human well being, but are not consumed at the expense of natural environment and future generations. In this storyline, institutions are effective, markets are universally regulated to internalize adverse environmental impacts, property rights are universally respected and poverty basically eradicated, as we know it today. The main motor of this high degree of equity and equality that preserves diversity in the world is the drive toward sustainable development and lifestyles.

Many of the now poor regions and social strata in the world achieve a conditional (and relative) catch-up partially through endogenous sources of development and partially through effective ODA and transfer of know how and know why through capacity building and learning. They leapfrog many of the development stages without ever even approaching the high consumption and emissions patterns of now developed parts of the world. This means that all parts of the world would achieve many goals of sustainable development by the end of the 21st century, leading to almost universal disappearance of poverty in the world. Like in the A1H&E storyline, the current distinction between "developed" and "developing" countries will no longer be appropriate in this scenario. In this storyline, now affluent regions of the world generally do not become much more affluent in terms of "physical" consumption, but indeed in terms of "virtual" and "dematerialized" consumption. Environmental and ecosystem protection rules. Geopolitically, this world could be described as "Pluralistic" and multipolar world of

[6] The B1H&E storyline is rooted in the SRES B1 scenario storyline (Nakicenovic et al., 2000). The emphasis on hydrogen and electricity and the broader narratives presented in this section (6.) are based on an earlier draft of the B1 storyline and quantification by Arnulf Grübler that dates back to 1998. It has been updated in the meantime to reflect some of the recent developments and scenario literature. We reproduce parts of this storyline here *verbatim* and use it extensively to develop the hydricity story. We are grateful for the explicit permission of the author to use this material in this report (Grübler, 2005b).

diversity of cultures and lifestyles with predominant global harmonization of environmental protection. It is a world where this stable political, economic and social order furthers sustainable development and equity to benefit of many.

The central elements of this storyline are high levels of environmental and social consciousness combined with globally coherent approach to sustainability based on a combination of lifestyle changes favoring quality over quantity and the development of "appropriate" and environmentally friendly technologies and settlement patterns. Heightened environmental consciousness might be brought about by clear evidence that impacts of natural resource use, such as deforestation, soil depletion, over-fishing, acidification, and climate change pose a serious threat to the continuation of human life on Earth. Likewise, continued economic disparities across and within regions are increasingly recognized as a threat to the sustainability of political and social structures as contributing to terrorism, conflicts, unrest, and vulnerability of societies and economies. Governments, businesses, the media, and the public pay increased attention to the environmental and social aspects of development. These changes in the ideation of the dominant development paradigm of the 20th century translate into changing perceptions, values, and preferences of private citizens and the public sector alike. The "slow food" movement, emerging at the end of the 20th century, serves as a guide for the global diffusion of "slow" lifestyles, in terms of diets, consumption and transport patterns, as well as attitudes towards the acceptability of new technologies.

There are many possible symbolic "images" of this storyline that can be captured by catch-phrases like: "Down to Earth", "Ecogarden", "Green & Clean", "Chat Room" (to denote virtual reality aspect of dematerializaton) or world of "Equity and Sustainability". An earlier catch phrase for this storyline was the "Dematerialization and Decarbonization" to denote rapid technological, institutional and social priority on environmental protection and sustainability as expressed by many stakeholder groups today. They portray the successful of sustainable development associated with the A1H&E storyline. The color image of this storyline might be green and down-to-Earth brown.

6.1. B1H&E Characteristics

The principal scenario driver is changing *perceptions, attitudes and lifestyles*, complemented by new models of international *policy coordination and cooperation*. Contrary to the prevailing trends towards consumerism and hedonistic lifestyles, "slow" and "smart" become the dominant metaphors for desirable lifestyles and technologies and are continuously critically evaluated and modified in view of a gradually evolving ideology of sustainability. While local and regional interpretations of sustainability vary, reflecting varied conditions, a widespread consensus on the imperative of sustainable development emerges across all societies and cultures. Sustainability fora and solidarity movements favoring the dis-privileged proliferate, enabled by rapidly expanding global communication networks and recast traditional "top-down" policy frameworks by "bottom-up" citizen movements. Talk is followed by action, initially based on grass-roots movements like NHI (No Hunger International) or HfA (Health for All), the objectives of which are increasingly adapted by national and international policy bodies translating into new models of international cooperation aiming at building the three pillars of sustainable development: eradication of poverty, social and economic equity, and environmental protection.

Dematerialization and Lifestyle Changes

Innovation and productivity gains are increasingly invested no longer in increasing consumption of the affluent but rather in improved efficiency of resource use ("dematerialization"), economic equity, building of social institutions, and environmental protection. Approaches are pragmatic and results oriented aiming at reconciling man and nature, i.e. means and ends are "Down to Earth". A strong welfare net prevents social exclusion on the basis of poverty within regions. An increasingly widespread social stigmatization of conspicuous consumption patterns results in rapidly changing lifestyles and increasing public support for stepped-up resource transfers from "rich" to "poor" also at the international level. Preservation and remediation become core themes of environmental governance, increasingly involving voluntary agreements, self-restraint, and "smart" technological solutions in addition to traditional command and control public policies. In a world of "global villages" values and lifestyles converge, whereas instruments (social and technological solutions) are increasingly varied to best reflect local circumstances. Harmony with nature and sustainable ecosystem services are a high policy priority reflected in individual and social values.

Despite this globalization of values and lifestyles, the focus of everyday life increasingly revolves around local communities. Whereas ideas are exchanged globally through increasingly sophisticated and cheap communication means, social contacts remain firmly rooted in local communities. "Down to Earth" citizens communicate and think globally, but live and act locally. For many, long-distance travel to remote destinations looses its traditional appeal, at best being a once-in-a-lifetime experience. Effective communication systems lead to emergence of "virtual" travel. However, counter-currents may develop and in some places people may not conform to the main social and environmental intentions of the mainstream as described in this scenario. Massive income redistribution nationally and internationally and presumably high taxation levels may also adversely affect the economic efficiency and functioning of world markets. The paramount importance given to "appropriate" technologies may hinder in some places the diffusion of advanced technology concepts such as fuel cell cars that might be objected in favor of environmentally benign bicycles. The quest for "sustainability correctness" may provoke counter-reactions, e.g. in form of "spring breaks" of students traveling 10,000 kilometers to distant holiday destinations. But despite these counter-currents, the sustainability paradigm gets established firmly and "think slow" and "smart" increasingly replaces "think big" as desirable goals for the material culture of societies.

Decentralization and Sustainability

Particular efforts are devoted to increases in resource efficiency to achieve the sustainability goals stated above. Incentive systems, combined with advances in international institutions, permit the rapid diffusion of cleaner technology. To this end, R&D is also enhanced, together with education and the capacity building for clean and equitable development. Organizational measures are adopted to reduce material wastage by maximizing reuse and recycling. The combination of technical and organizational change yields high levels of material and energy saving, as well as reductions in pollution. Labor productivity also improves as a by-product of these efforts. Combined with the quest for high quality of product and services this translates into high productivity gains and into hefty increases in high value added activities and products, yielding high economic growth.

Accordingly, B1H&E storyline specifies more emphasis on decentralized energy conversion, distribution and energy end-use patterns. The world is also more urbanized than today but the patterns are assumed to be fundamentally different. They would be more consistent with widespread of urban sprawl into smaller settlements and communities. These are also interconnected through sophisticated infrastructures, but are fundamentally more autonomous and autarkical. The scenario places great emphasis on environmental protection at all scales, from local to global. It is representative of a successful implementation of sustainability together with a more equitable society. This implies that there is a substantial degree of income redistribution in space and time (another important maxim of the sustainability transition). As such, the scenario illustrates a complete paradigm change compared to current inequalities and environmental destruction. Another salient aspect of this scenario is the implicit change in lifestyle and social priorities.

6.2. B1H&E: Key Drivers

Population, economic development, and regional disparities

The demographic transition to low mortality and fertility occurs rapidly; incidentally at the same rate as in high economic growth A1H&E storyline presented above, but for different reasons as it is motivated partly by social and environmental concerns. For instance, reducing the environmental "footprint" of humanity is increasingly stated as reason for low fertility levels. Sub-replacement fertility levels ranging between 1.3 to 1.7 children per woman are a globally pervasive phenomenon. Global population reaches nine billion by 2050 and declines to about seven billion by 2100.

B1H&E storyline describes a world with high levels of sustainability. The corresponding SRES B1 scenario family describes a development pattern in which global GDP would increase to some \$50 Trillion by 2020, \$140 Trillion by 2050, eventually multiplying by a factor close to 20 by the end of the 21st century (to some \$350 Trillion). But nature of economic activities and especially its distribution are radically different from conventional high economic growth scenarios. High value added increasingly does not rely on resource consumption as a high proportion of income is spent on services rather than on material goods, and on quality rather than quantity. Personalized services, revival of (expensive) arts and craft custom-made objects, cultural activities all add high value to the "green" GDP, without however requiring large natural resource inputs. The economy and consumption patterns become increasingly dematerialized. The emphasis on material goods decreases as resource and waste disposal prices are increased by environmental taxation.

Another important difference is in the more equitable income distribution, both domestically as well as internationally. Global income disparities when measured by per capita income differences between "North" and "South" were approximately 16:1 in 1990 when incomes are compared at market exchange rates, and still a factor close to 6 when incomes are compared at purchasing power parities. These income disparities are significantly reduced in the "Down to Earth" scenario as a result of deliberate progress toward international and national income equality. North-South income disparities (expressed at market exchange rates) would be reduced to a factor of 4:1 by 2050 and a factor 3:1 by 2100 (and to a factor of 1.5 when incomes are compared at purchasing power parities).

Social Trends and Governance

As mentioned above, *social change* is the principle characteristic and main driver of this scenario. Trans-material values and lifestyles become a global phenomenon, but unlike the traditional Western consumerism model these new lifestyles emerge out of a multitude of sources and in a polycentric structure, drawing inspiration from a wide variety of experiences from religion, philosophy, as well as concrete life biographies from all over the world. From this perspective, the "slow" movement is different from the "green" movement of the 20th century and hence might find much wider adoption.

The material culture of people is not necessarily frugal, as people continue to value highly their indoor and outdoor environments, albeit always emphasizing quality over quantity. Instead of "throw-away" products, longevity, repair capability, and perfect functional and artistic design become the dominant purchase criteria. Minimization of up-front expenditures (e.g. in housing) gives way to a systematic life-cycle economic perspective, fully considering externalities and placing paramount priority on environmental performance. With the exception of demonstrative, conspicuous consumption products such as luxury cars or private jets, which are considered undesirable, material consumption patterns allow for plenty of choice. Lifestyles emphasize *ludique* over social status via demonstrative consumption. Fashion designers, ebonists, even builders of wooden sailing boats are all professions that see a vigorous revival as consumer demands and lifestyles change.

Also the spatial context in which people's lifestyles take place changes significantly. Instead of spatially separated activities, collocation and "community" become important spatial foci of every day life, significantly promoting "soft" mobility and reducing long-distance travel demand. The "think globally, act locally" philosophy is applied in a system of electronically interconnected "global villages", in which both traditional rural and suburban villages coexist with "urban villages", that have high population densities, but otherwise function economically and socially like traditional village communities (a contemporary example being Greenwich Village in New York).

Governance structures are effective in this scenario at all levels from the local up to the global. They are participatory and pluralistic. Regulatory modes are diverse and generally take considerable amount of time, coordination, and approval seeking, not at least because of the grassroots type nature of many social movements involved as stakeholders. However, whatever time is lost in the policy formulation process, is quickly gained subsequently by wide social "buy-in", fast implementation and limited obstruction to regulatory rules.

A distinguishing feature of B1H&E storyline (as well as similar scenarios portrayed in the scenario literature) is the emergence of effective international governance. Originally emerging out of the environmental field, global governance structures and institutions progressively extend their reach to include for instance, technology policy (R&D and standard setting), IP rights, education, even media control. These tendencies materialize first in highly concentrated sectors, such as aviation or the automobile industry. For instance, the Global Aviation Advisory Board (GAAB) is instituted by a UN resolution in 2015 and as of 2020 sets global standards for the safety, fuel efficiency, and emission performance of all aircraft designed and operated. GAAB also has to power to "ban" outdated technological vintages, accelerating the turnover of capital stock and thus the diffusion of new types of aircraft. Yet, by 2050, environmental pressures, especially in connection to climate change trigger even stiffer regulation affecting also consumer choice through the introduction of air ticket quotas that are originally auctioned-off, but subsequently allocated on a per-capita basis.

Another area of intense regulatory arrangements is personal mobility. Local and shorter distance individual travel is important because of the lower population densities and distributed settlement patterns. In many communities, the preference is for using bicycles and "collective taxis" instead of cars. However, advanced generation of hydrogen hybrid vehicles is increasingly used to distributed electricity and heat production. Cars are connected to individual houses. Their fuel cells and batteries help manage the load across local micro-grids. Houses are already close to zero-energy. Such elaborate systems for reducing material-intensiveness of the economy and emissions require widespread regulation and coordination in real-time. The regulatory frameworks are basically oriented toward "virtual" systems integration and re-bundling.

Regulation deepens in all aspects concerning social equity and environmental protection. Even if benign in intent, the consequences of this "Big Sister" state are perceived by many as overly patronizing and jeopardizing civil liberties. Thus all governance institutions are continuously challenged and are in permanent need for justification and seeking wide stakeholder consensus. This is the necessary price to pay to get wide approval of the ambitious projects of international resource transfers (reaching up to five percent and more of GDP of the donor countries) being part of the global war on poverty or for the exorbitant carbon taxes introduced to combat climate change (rising from around $50-100 per ton carbon in 2010/2020 to some $2000 per ton towards the end of the 21st century).

Environment and Ecology

Given the high environmental consciousness and institutional effectiveness assumed for this scenario, environmental quality is high, as most potentially negative environmental aspects of rapid development are anticipated and effectively dealt with locally, nationally, and internationally. Clean local water and air are first policy priorities and an almost universal global provision is achieved by 2030. Transboundary air pollution (acid rain) is also basically eliminated in the long term. Land use is managed carefully to counteract the impacts of activities potentially damaging to the environment. Cities are compact and designed for public and non-motorized transport, with suburban developments tightly controlled. Strong incentives for low-input, low-impact agriculture, along with maintenance of large areas of wilderness, contribute to high food prices with much lower levels of meat consumption. Agricultural activates resemble more a "technogarden" in harmony with natural ecosystems.

Overall, all negative impacts of an industrial society are at the focus of public and citizens attention. If technological solutions can solve the problem they are adopted, assuming they meet the criterion of local social appropriateness (e.g. zero-emission vehicles in industrialized countries). If no technological fix can be devised or the technological solutions are deemed insufficient (like for measures reducing aircraft noise) the answer is a strict ban on activities or technologies deemed socially or environmentally undesirable.

Box: Making Cheaper Hydrogen

Hydrogen-powered fuel cells provide efficient, reliable and clean power for everything from buildings to vehicles and wireless devices in the A1H&E and B1H&E storylines. Today, about 6 EJ of energy are in the form of hydrogen worldwide, but most of this hydrogen is produced by steam reforming of methane. This is the cheapest way of obtaining hydrogen but it is much more expensive than other energy carriers such as electricity. Other, even more costly method of producing hydrogen is through electrolysis of water. First, electricity needs to be generated and than hydrogen, leading to both high costs and low conversion efficiencies. These practices are so expensive that many argue that hydrogen era is decades away. One method of reducing the costs of hydrogen in the hydricity age is by improving catalysts employed in many of the hydrogen-producing reactions. Common catalysts today include precious metals like gold and platinum. Some have even raised concerns that the future age of hydricity may transform the current dependence on oil to future dependence on precious metals.

Recently, researchers at the University of Wisconsin-Madison have constructed a catalyst from nickel, aluminum, and tin that could be hundreds of times less expensive and still accelerate reactions involving production of hydrogen from methanol or biomass. These catalysts would provide for cooler reactions requiring much less energy compared to steam reforming today. This could conceivably make decentralized hydrogen energy cheap enough that commercial buildings, homes and cars cold have their own power supplies (Dizikes, 2004).

One notable exception to this approach is in the efforts to combat[7] climate change. Avoiding climate change impacts in promoting a vigorous move towards a carbon-free energy system is recognized to be feasible only over the long-term. Because of the pervasiveness of energy use activities the simplistic "ban away" approach is simply not feasible, requiring instead a whole host of positive and negative incentives in terms of R&D subsidies, clean technology and clean development funding as well as taxation of emissions, which are gradually, but persistently stepped up reaching $2000 per ton carbon. As a result, towards the end of the 21st century the task of phasing out fossil fuels is well underway and atmospheric concentrations of CO_2 are stabilized at below 450 ppmv.

This kind of accelerated decarbonization of the energy system requires new development priorities and paradigms. This is why we assume a whole host of different policies and measures geared toward decarbonization. We do not assume a "single silver bullet" but rather a whole portfolio of policies that leads to a vigorous portfolio of mitigation measures.

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[7] This is a notable difference to the SRES-B1 scenario that assumed no explicit climate policies. It is more consistent with the Post-SRES B1-450 stabilization scenario and the B1T high-technology variant of the basic storyline.

Box: Photobiological Hydrogen and Green Algae as Source of Hydrogen

Green algae have the unique ability to convert water and sun into hydrogen through the process of photosynthesis. Large-scale renewable hydrogen could be produced from mass cultures of (genetically) modified green algae. In principle, this could one day provide commercially viable source of renewable hydrogen. Assuming optimal conditions, it is conceivable that green algae could produce up to 20grams of hydrogen per m^2 culture area per day. But this optimistic scenario cannot be realized with present day know-how.

Other more advanced methods of direct photobiological hydrogen production are also being studied (NAE, 2004). Hydrogen production by direct oxidative cleavage of water, mediated by photosynthetic (micro)organisms, without biomass as intermediate, is an emerging technology at the early exploratory research stage (Gregoire-Padró, 2002). By circumventing biomass formation and subsequent gasification, the yield of solar energy conversion to hydrogen by direct photobiological processes is theoretically more efficient than is biomass gasification by 1 to 2 orders of magnitude. The direct photobiological hydrogen release could be on the order of 10 percent, compared with efficiencies of between 0.5 to 1 percent for biomass-to-hydrogen conversion. It is conceivable that bioengineering efforts on the light harvesting complex and reaction center chemistry could improve this efficiency several-fold over the coming decades, and thereby bring the overall efficiency (solar-to-hydrogen) of direct photobiological hydrogen production into the range of 20-30 percent. However, substantial, fundamental research needs to be undertaken before photobiological methods for large-scale hydrogen production are considered (NAE, 2004).

Resources and Technology

With a few exceptions of environmentally critical raw materials, resource availability becomes progressively decoupled from geology and ecology. In other words, not geological availability determines resource availability, but rather *social choice*. Despite continued abundance of coal and unconventional oil, few deposits are explored and even fewer exploited as efforts concentrate to achieve a smooth transition to alternative energy systems.

There is extensive use of conventional and unconventional gas as the cleanest fossil resource during the transition (also used as transitional fuel for cars, buses, and aircraft), but the major push is toward post-fossil technologies centering around the twin energy carriers electricity and hydrogen, driven in large part by environmental concerns. This hydricity transition is made the easier, because demand remains relatively low, reflecting pronounced dematerialization of economic activities, changing consumer choices, as well as high prices. As a result global energy use only grows slowly, roughly doubling by 2050 and quadrupling by 2100 -- for an almost 20 times increase in the size of the global economy. Conservation and efficiency are the maxims of this future society.

Box: Utsira project

A pioneering project on the island of Utsira in Norway envisages that ten households to be supplied first by wind electricity and eventually also hydrogen produced from wind power.

Utsira is a remote, wind-swept island off the west coast of Norway. This small island community with 240 inhabitants is where one of the most innovative projects ever developed by Hydro of Norway and its partners will be tested. The basic idea is to provide fossil-free electricity and hydrogen on the whole island and thereby make it energy sufficient and virtually emissions free.

Utsira is very windy so that the two wind turbines with installed capacity of 600 kWe each can in principle produces power in excess of the community's electricity demands. However, wind power is not necessarily available when needed and excess production during periods of strong wind would need to be wasted. To resolve this potential mismatch between supply and demand, Hydro has decided to store excess energy in the form of hydrogen. Electrolysis will be used to produce hydrogen for storage and a hydrogen internal combustion engines and a fuel cells will be used to convert the hydrogen back to electricity when needed.

The unique aspect of the Utsira project is that its energy system will be virtually closed. The ten households will receive all their electricity from wind without backup generation or electricity imports. As the power consumption of the islanders varies, hydrogen will be either produced or the stored hydrogen will be converted back into electricity. Only once hydrogen storage is full the excess energy would be sold on the electricity market.

The Ulisra project is one of the first decentralized "hydricity" system for a whole community. It is a precursor of the energy systems envisaged in the B1H&E storyline.

Energy systems diversify out from the use of fossil fuels. By 2020 close to 20 percent of global energy supply are derived from zero-carbon energy sources, a share that increases to 30 percent by 2050 and well over 50 percent perhaps even 80 percent by 2100 alleviating both pressures on depleteable resources as well as on the environment.

Technologically, the scenario is characterized by high levels of technological development in the domains of material and energy saving, emissions control technology, as well as labor productivity. The latter is essential to support the rapid growth in personal income, given that a major increase in labor force participation is implicit in the equity assumptions of rapid economic growth in the "South". Technologies tend to be implemented in a pollution prevention mode, implying a much more highly integrated form of production than industry practices today.

The traditional competitive model of technological innovation gives gradually way to elaborate schemes of informal and formal coordination of R&D activities. Overall, both public and private sector R&D expenditures are significantly stepped up (reaching up to 5 percent and more of GDP), but increasingly targeted to environmentally desirable technologies in the domains of pollution prevention and environmental restoration but always being anxious about unintended side-effects. As a result, technology and risk assessment become dominant professions, not unlike lawyers in the contemporary US.

Box: Iceland's Road to Hydrogen Economy

Hydrogen is being tested in many buses from Amsterdam to Vancouver as a clean source of energy to replace oil products and thereby reduce emissions. There are three fuel cell hydrogen buses operating in Reykjavik. “Sometimes I have to explain to passengers that it's just water vapor,” the driver said of white clouds trailing after his bus along the streets of Reykjavik. “When it's very cold there's a lot of white steam.” (Doyle, 2005)

About 70 percent of Iceland’s energy is renewable from geothermal sources and hydropower. The only exception are road, air and water transport. Like everywhere transport depends on liquid oil products. Other important source of carbon emissions in Iceland is aluminum smelters. Even though the electricity is renewable and carbon free, the smelting process itself emits CO_2. Thus transport and aluminum industry are the major source of carbon emissions.

Some consider hydrogen as the future clean energy carrier of choice for Iceland. In conjunction with renewable sources of electricity, renewable sources of hydrogen would bring the hydricity age closer to home and would at the same time drastically reduce Iceland’s carbon emissions. To power the hydrogen buses, Iceland has installed a hydrogen gas station in Reykjavik. Hydrogen is produced through electrolysis of water. The only drawback is that the fuel thus produced is relatively expensive compared to the polluting alternative, the diesel. Iceland's buses, made by DaimlerChrysler, cost about €1.25 million each, or three to four times more than a diesel-powered bus, It takes about 6-10 minutes to refill a hydrogen bus, giving a range of 400 km. A further advantage of hydrogen busses is that they are far less noisy compared to their diesel counterparts.

Furthermore the great Icelandic fishing fleet is a candidate for hydrogen production because it accounts for about 30 percent of the Icelandic oil imports. In the long run the whole public and private transport will be transferred to hydrogen produced on the basis of renewable primary energies (Hydrogen Mirror, 1998).

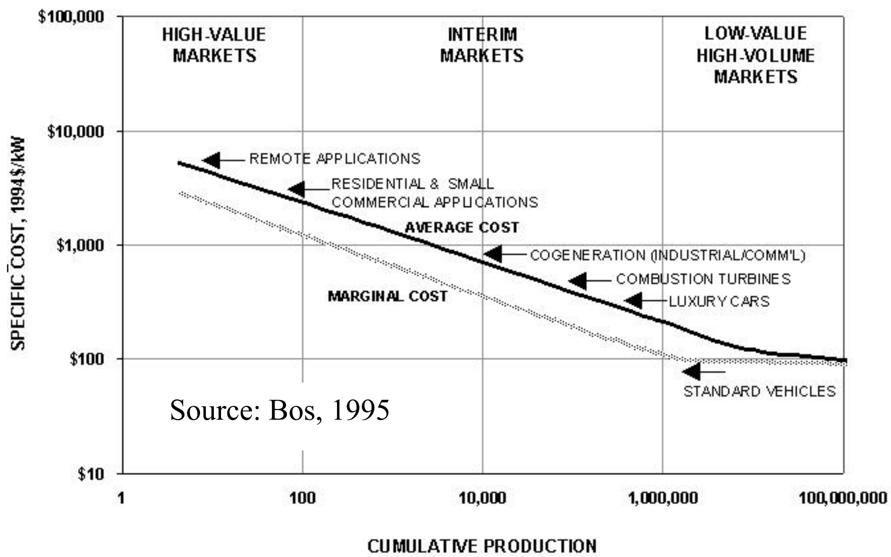
Iceland is very vulnerable to climate change being located in the North Atlantic. Many consider further melting of glaciers a virtual certainty. This would release huge amounts of water that could be used to generate a lot of electricity. Unfortunately, electricity cannot be stored and is notoriously difficult to transport over large distances. Iceland itself is too small to be able to utilize so much electricity. A futuristic idea is to convert the electricity to hydrogen in the long term future and ship it to Europe or North America. This would make Iceland a net energy exporter and perhaps the first to offer large amounts of zero-carbon energy carriers on the world market.

Communication and Transport

Communication and transport act as substitutes especially after the emergence of full virtual reality (VR) personal communicators that manipulate and enhance brain functions for a perfect multimedia experience, including sound, vision, smell, tastes, and tactile experiences. The phenomenal corresponding growth in bandwidth is managed via new carbon nanotube cables and ubiquitous satellite connections. These advanced information technologies achieve a global spread quickly, and are fully integrated into all economic and social activities. Much like the almost universal and 100 percent adoption of mobile phones among the youngsters in Europe, VR personal communicators and their early precursors are globally adopted.

Box: Diffusion Hydricity Vehicles

Fuel cells and other hydrogen technologies are prohibitively expensive and have penetrated only a few specialized niches such as space shuttle, few stationary applications and experimental buses and cars. This is likely to continue to be the case during the coming decades. Assuming even an optimistic learning curve for the improvement of fuel cells (as illustrated in the figure, see Bos, 1995), it would be necessary to install many GW of fuel cell before their costs can come in the vicinity of internal combustion engines. First applications are likely to there where high costs might be acceptable such as on remote locations, in congested urban area. Another large market are mobile electronic devices or a new generation of "virtual assistants" that might integrated many of the current mobile devices from a telephone and a laptop to an electronic office. Ultimately, advanced micro, nanomachines and specialized robots might become dependent on hydricity as a source of energy in conjunction with fuel cells. These are many possibilities and potential niches for more widespread diffusion of fuel cells.



The largest market fuel cells are automobiles. There are some 700 million cars in the world. With installed capacity of say 70kW each, this corresponds to some 50TW of installed capacity, well over ten times all power plants and other generating capacity taken together. Even with modest learning curves, such huge capacity will certainly drive costs down should fuel cells ever power vehicles.

Fuel cell cars will most likely be of a hybrid type including some form of on board electricity storage. They would range from small vehicles including (fuel-cell)cycles to buses. Applications are also potentially large in hydrogen aircraft to produce onboard electricity.

The "global communication panel" report of 2050 identifies that out of the 9 billion people inhabiting the planet in 2050, less than 500,000 refuse the use of a VR communicator out of privacy concerns. Even the most critical technology luddists embrace fully the increasingly wide range of advanced electronic communication technologies and infrastructures, as they epitomize dematerialization and "smart" use of resources. Electronic communication also provide for the only technological mean to cope with the complexities of participatory decision making processes. Cynics postulate a "law of constant voting time" of approximately two hours a day which many consider as taxing and ineffective. Conversely, electronic communication turns out to be quite effective in substituting for travel demand. As a result both travel time and money budgets get significantly reduced.

Box: Distributed Systems Integration and Settlement Patterns

Large potential synergies exist through systems integration and virtual coordination. Zero to very low energy houses provide an ideal integration environment for hydricity vehicles. This is especially the case in the B1H&E storyline because of low population densities. Cars could be integrated into the house to cogenerate heat and power locally from hydrogen (either distributed through pipelines or stored locally). Such cars would become a decentralized power systems both for production and (short-term) storage of electricity. This scheme would harmonize really well with renewable sources of hydricity, whether local photovoltaic and wind systems or direct hydrogen production through genetically engineered photosynthesis. Integrated house-car systems could both manage hydricity loads through generation, conversion of hydrogen to electricity (and vice versa) and through hydricity storage. Clearly, such systems would require virtual planning and real-time coordination (as a "distributed" grid). For example, the use of the hydricity vehicles would be connected with some kind of "opportunity" loss when disconnected from the virtual grid. As cars are not used most of the times, this is more a question of logistics and coordination.

Transportation demand grows only slowly with air transport being the most hit by "Down to Earth" consumers. Walking (including jogging), bicycles and zero-emission vehicles are used locally with little need for very long distance travel. In the near-to medium term there remains some room for modest growth of long-distance mobility particularly in developing countries (perhaps a factor two growth to 2020 and a stabilization at that level to 2050), but over the long-term air transport volume declines in absolute amounts compared to present day levels. Other long-distance transport modes fare only somewhat better, especially when perceived as environmentally less obtrusive, such as conventional rail. Under a general "slow" movement philosophy the market potential for high-speed ground transportation (maglev's) remains low: a few isolated lines are built in particularly dense urban corridors (Shinkansen, Beijing-Shanghai, BosWash, Rio-Sao Paulo), but these remain isolated infrastructures and see no pervasive diffusion. Local transport modes emphasize "soft" mobility concepts by public transport and bicycles (many of them fuel cell powered) and by small fuel cell carts in suburban settings. Traditional cars survive only in truly rural areas, where they are either an integral part of the house (source of power and storage facility) or continuing to rely on gasoline for many decades, especially in developing countries. However, over the long-term virtually all rural vehicles become hydrogen powered, produced decentrally to avoid obtrusive large energy infrastructures.

7. Hydricity Energy System

Improvement of human well being is the salient driving force leading towards the larger role of abundant, affordable, convenient, cleaner and more environmentally compatible energy services and the possible emergence of the "Hydricity Age". Central to this strategic vision a world in which partnerships and alliances must be built with private and public stakeholders to mitigate the risks of climate change and to achieve sustainable development.

During the last two centuries, global energy systems have transformed from a reliance on carbon intensive sources of energy such as coal to oil and more recently to natural gas. This has resulted in substantial decarbonization of global energy. Diffusion of electricity and energy gases was an essential towards pervasive decarbonization. The energy gases started with synthetic, manufactured gases, but exploration and production activities of the gas industry during the 20th century has enabled natural gas to become the fuel of choice (and thus contribute to the decarbonization of energy). Electricity has emerged as the other clean energy carrier of modern societies and a crucial part in provisioning of energy services from mobility to information. Enhanced decarbonization is indeed an important driving force for the further diffusion of electricity and hydrogen.. A larger role of hydrogen would be consistent with this trend as well as with the need to reduce the emissions of greenhouse gases that are associated with anthropogenic sources of climate change. Expanding the use of gas today and hydrogen tomorrow is the best response to the threat of climate change.

Another driving force is the need for clean and affordable energy services. Access to affordable energy services is crucial for economic development with more than 1.3 billion people living in poverty (with less than $1 per day) and with two billion without access. In general, a larger role of electricity and energy gases in developing countries would help towards meeting their needs for energy services and towards reducing adverse environmental impacts from indoor air pollution to regional acidification. Asia, in particular, where the emerging markets of China and India between them account for a third of the world's population, is expected to experience a surging need for clean and affordable energy services that can be provided by electricity and natural gas in the medium term and hydrogen in the long run. The two hydricity storylines give alternative roadmaps toward this long-term goal of adequate and affordable energy for all with close to zero greenhouse gas emissions.

The need for energy services is inseparably linked with cities and their people. Without addressing these connections, efforts at urban management and planning are destined to end up in failures. Conversely, the structures of future cities and the dynamics of people's lifestyles, have serious implications for energy systems. These are some of the findings of the two hydricity storylines, one envisages further urbanization leading large megacities and conglomerations of urban areas, while the other emphasizes smaller communities and decentralized settlement patterns. Both of the storylines indicate a further need for inter-disciplinary approach in assessing various dimensions of hydricity age and human well being spanning the fields of energy, urban planning, economy, technology, ecology and climate. The storylines hint at many facets of sustainability ranging from liberty, equity, identity and governance to issues of land scarcity, urban sprawl, habitat and species loss, traffic congestion, air and water quality and waste disposal. They provide a potential diversity of solutions, one emphasizing more integrated and centralized solutions while other the decentralized and local ones.

The diversity of development paths illustrated by the two storylines demonstrate that the provision of human needs should be tailored precisely to the unique characteristics of each particular location and environment. Even the global and integrated aspects of A1H&E storyline build on unique local and regional characteristics. The many important economic, environmental and societal dimensions of development and sustainability together with their global and local contexts provide a huge opportunity for the hydricity technologies in the two storylines. Clearly, the materialization of some of the tendencies spelled out in the two storylines are not autonomous as they depend on decisions which have not been made yet. They required dedicated and cumulative investments in human capacity, institutions, technology innovation and diffusion, and in infrastructures ranging from energy to human settlements. On the downside for the hydricity future, there are plenty of scenarios in the literature where hydrogen remains to be elusive energy carrier. Clearly, hydricity age is not a must but rather an opportunity towards a more sustainable future.

The perceptions about hydrogen as an energy carrier have changed during the last decades. They range from overoptimistic hypes associated with early and rapid introduction of fuell cells to strong pessimism because of the high costs of hydrogen production, difficulties with storage and transport and most of all because like the electricity the need to produce hydrogen from different sources of energy. Potential energy sources for the hydricity age range from renewables and nuclear to fossils in conjunction with carbon capture and storage. Resource constraints are not imminent over a century scale and perhaps longer. For example, methane hydrates are so vast that they would render natural gas into a virtually inexhaustible source of energy. The concerns are more in the area of security, adequate investments and environmental burdens.

A crucial challenge for the emergence of the hydricity age is to develop global and regional production and trade in hydricity generated from many diversified sources through dedicated investment in infrastructures. While technological improvements may reduce the capital investment levels required as anticipated in the two storylines, the ultimate decision in terms of energy mix will depend not only on prices but also stability of supply, energy security and environmental considerations. Asia is likely to become one of the major hydricity markets.

The two storylines indicate the magnitude of the challenge for the transition toward the hydricity age to be very similar to that hundred years ago for the introduction of electricity. The opportunities and barriers for hydrogen and more generally hydricity appear to be very similar in the two scenarios. Hundred years ago, electricity generation was prohibitively expensive, less efficient than more direct use of coal (in steam engines as a prime mover or for heat), it required enormous investments in infrastructures and adoption of fundamentally new end-use devices. All of this is true today for hydrogen and hydricity. In the two storylines, the emergence of the hydricity age brings multiple benefits, from clean and zero-emissions energy carriers, to decarbonization and convenience. Storylines regimentally describe the convergence of some new technologies and services that might be enhanced or even made possible with hydricity. The same was true for electricity during the last century. It made new human activities and energy services possible that were unattainable before. Computers and intercity trains cannot be powered directly by coal, nor can the modern services-oriented societies. Virtually all human activities depend today on the availability of affordable and reliable electricity virtually everywhere. In the two scenarios, hydricity services promote the convergence of nano, bioengineering, cogno and advanced information technologies into fundamentally new products and services. Hydricity economy holds the promise of containing carbon emissions and fully decarbonizing human activities and thus avoiding the potential dire consequences of climate change.

The message of the two storylines for the energy industry and governments is for decisions to be clearly articulated to enable the selection and integration of energy infrastructure to proceed with confidence. However, this also implies huge investments required first for achieving more vigorous research and development and later for building new infrastructures and energy systems. These needs are estimated in many scenarios in the literature. The SRES scenarios result in infrastructural and energy investments of some $300 to 500 billion per year during the next 30 years, half of those being needed for expansion of distribution systems. Infrastructural investments also include storage facilities both for energy gases, electricity and for carbon.

Stationary uses of energy gases for cooking or in fuel cells for electricity generation are important for many developing countries that do not have universal access to electricity today. Higher shares of natural gas as (public) transport fuel would be another priority as it can result in a substantial reduction of urban air pollution. Fulfillment of these large technology needs would require closer collaboration among many countries and close industry and public partnerships especially to develop energy infrastructures such as pipeline grids and to develop and deploy new energy technologies. Governments have the primary role in creating the necessary legal and regulatory conditions in the development of gas markets, especially in smaller customer markets, as well as for the quality and efficiency of the service that should be guaranteed. These are some of the shorter-term enabling developments that are a consistent with the long-term transition toward hydricity in the two storylines.

Fuel cell technologies are considered to be an important and essential component of future energy systems in both storylines and would play an essential role in improving natural gas uses and beyond in conjunction with hydrogen. Fuel cells are a generic technology as there are many types, from low to high temperature, from mobile to stationary. What they have in common is modularity and the possibility of small-scale distributed generation of electricity and cogeneration of heat. This is a decisive advantage as it may lead to substantial cost buy-downs along learning curves and render this technology economical in coming years and decades. The challenge today is the high cost compared to other alternatives, such as the internal combustion engine for automobiles. For example, including fuel cells in newly built houses could meet the environmental objectives of reduced energy use and emissions, while providing an early market for a high cost product. However, it appears that no major technical breakthroughs are required before fuel cells can be introduced into the stationary energy sector – although a lot of engineering development and especially cost reduction will be necessary. In the automotive sector the challenges are perhaps greater, as transport is much more homogeneous than power or heat generation in terms of both fuel use (only gasoline or diesel in significant quantities) and the ubiquitous internal combustion engine. So the introduction of the fuel cell to meet environmental goals also requires changes in fuel provision, and the simultaneous development of both fuel cells and infrastructure. Fuel cells are expected to be one of the core technologies for motor vehicles in the 21st century as an integral component of the hydricity age.

In the meantime, the so-called bridge technologies, such as hybrids, compressed natural gas, bio-fuel, GTL and DME vehicles would diversify the fleet, help reduce emissions and provide enabling infrastructures for fuel cell vehicles with hydrogen propulsion in the very long term. Emissions free or close to emissions free vehicles will be required as mobility continues to increase during the century. The two storylines spell some of these salient developments in individual mobility.

A larger role of energy gases and electricity in the two storylines means these two energy carriers would also account for an even higher share of global emissions of greenhouse gases and especially carbon dioxide. This means that some of the technologies for carbon capture and storage would need to be developed and deployed. Already today, carbon dioxide is separated and stored in a deep sea aquifer below the North Sea (Sleipner and Snowhit gas fields) and carbon dioxide serves as an agent for enhanced hydrocarbon recovery. However, very high levels of carbon taxes would also make carbon capture from coal more economical as well as the introduction of nuclear and renewable energy sources for conversion to hydricity.

The amounts of carbon dioxide to be stored would be truly enormous, ranging from a few to perhaps even more than 500 GtC (billion tons of elemental carbon) cumulated by the end of the century. The potential storage capacity in underground aquifers, depleted oil and gas fields and underground coal mine seams are all large and would suffice for storing captured carbon. The exhausted oil and gas fields represent a particularly good medium for carbon dioxide burial and storage. At the same time, injection of CO_2 can enable enhanced production of residual oil, gas and gas condensate. Oceans are today one of the largest carbon reservoirs and could potentially store vast amounts in the future, but this option is very controversial because of the uncertain environmental and ecological impacts. Humanity has changed global climate during the last two centuries so that we are already beyond the point where a new energy regime and transition is required. Carbon capture and storage in conjunction with renewables and possibly also nuclear energy could in principle reduce global carbon emissions to virtually zero. Hydrogen and electricity could become pollution-free and renewable energy carriers. Achieving a hydricity age has never been more urgent.

Today, the economics of hydrogen as an energy carrier are unfavorable, primarily because the external costs associated with the impacts of climate change are not considered in the cost calculations. However, once these external costs are included, the situation might change significantly. This is an argument for why governments should play a greater role in providing the necessary frameworks and incentives. There has already been a move towards the experimental use of hydrogen in buses and other end-use devices. Usually, natural gas is a source of hydrogen. Other possibilities have been tested as well. For example, in Iceland geothermal and hydropower are used to produce hydrogen.

Today, methane steam reforming is the most economical route for hydrogen production. Industry has considerable experience with hydrogen production by methane reforming, which can be seen as the transition route to the hydricity age. Unfortunately, the economic opportunities for carbon capture and storage are only possible on a large scale. Another challenge is how to make small-scale reforming technology cheap and reliable, especially for use in refueling stations or on board vehicles. First steps in this direction already exist. Another possibility during the transition toward the hydricity age would be to mix hydrogen and methane (hythane), which would reduce carbon emissions to the atmosphere and would not require new pipeline and distribution grids. In the medium term, there would be an opportunity to develop small hydrogen distribution networks for stationary fuel cells producing heat and power, and refueling stations for hydrogen fuel cell vehicles.

Central hydrogen production with steam reforming of methane in conjunction with carbon capture and storage and from intermittent renewable sources, such as wind and hydropower, and the development of hydrogen transmission and storage are expected only in the much longer term. Thus, there are many possible technological synergies between hydrocarbon energy sources (in conjunction with carbon capture and storage) and renewables as complementary sources of electricity and hydrogen. The gas and electric industry should participate in the development of such perspectives in order to better understand what this could mean in the future.

All of the infrastructure and technology requirements imply high R&D needs. Some of these are not necessarily the highest priority for the more developed regions of the world, e.g., technologies for efficient conversion of biomass cellulose into energy gases. Public and private partnerships are essential for achieving these challenging development needs. The energy world is entering a fundamental transition that is characterized by liberalization of markets, an increasing need for safety and energy security, and concerns about climate change. At the same time, the demand for services is likely to double many times by the end of the century. The diffusion of new and advanced technologies is a corner stone of this transition. The highest technological priorities are concerned with the reduction of carbon dioxide emissions through carbon capture and storage, the production of hydrogen as an emissions-free energy carrier and the development of affordable renewable sources of energy, safe and proliferation-resistant nuclear energy and vast unconventional resources of hydrocarbons such as the methane hydrate deposits. In contrast to these large technology and resource development needs are the declining public R&D efforts throughout the OECD countries and the ever increasing competitive pressures facing the natural gas industry that further reduce the availability of R&D efforts. Public and private partnerships for technology innovation are essential for paving the road toward the hydricity age. Further, governments should provide strong support for research and development (in technology but also in socio-economic disciplines), with fiscal and policy incentives for demonstration projects. Governments should not try to pick the "winners." However, very clear policy objectives must be articulated so that appropriate technologies are chosen. This will require a vision of the future. Facilitating energy investments and promoting R&D are two of the major challenges on the road towards a hydricity age.

For hydricity age to become a reality a whole host of new technologies needs to be developed and deployed at affordable prices. They would also need to be socially acceptable and safe.

Finally, the vision of a hydricity age provides a perspective towards future zero emissions energy systems with universal access to energy services by all.

References

Alcamo, J., A. Bouwman, J. Edmonds, A. Grübler, T. Morita, and A. Sugandhy, 1995: An evaluation of the IPCC IS92 emission scenarios. In *Climate Change 1994, Radiative Forcing of Climate Change* and *An Evaluation of the IPCC IS92 Emission Scenarios,* Cambridge University Press, Cambridge, pp. 233–304.

Barreto, L., A. Makihira, and K. Riahi, 2003: The hydrogen economy in the 21st century: a sustainable development scenario. International Journal of Hydrogen Energy 28(3), 267–284.

Bos, B. P. B, 1995: Commercializing Fuel Cells – Managing Risks, Fourth Grove Fuel Cell Symposium, Commonwealth Institute London, September 19–22, 1995.

Dizikes, P., 2004: Making Cheaper Hydrogen, *Technology* Review, December 2003/January 2004.

Carpenter, R. S., P. L. Pingali, E. M. Bennett, M. B. Zurek (eds.) 2005: *Ecosystems and Human Well-Being: Scenarios*, Vol. II, Findings of the Scenario Working Group, Millennium Ecosystems Assessment, Island Press, Washington DC, USA.

Doyle, A., 2005: http://www.reuters.co.uk/newsArticle.jhtml?type=worldNews&storyID=650773.

Goldemberg, J. *et al.*: 2000: World Energy Assessment Overview, *in* Energy and the Challenge of Sustainability, *World Energy Assessment Report*, Goldemberg, J., Anderson, D., Holdren, J.P., Jefferson, M., Jochem, E., Nakićenović, N., Reddy, A.K.N., Rogner, H.-H. *et al*. (eds.), UNDP, UNDESA, WEC, New York, NY, USA.

Grégoire Padró, C. E., 2002: "Hydrogen from Other Renewable Resources," National Renewable Energy Laboratory, presentation to the National Academy of Engineering, Board on Energy and Environmental Systems, December 2, 2002.

Grübler, A., 2005a: "Scenario A1 Storyline or Tiger World", private communication based an unpublished draft paper.

Grübler, A., 2005b: "Scenario B1 Storyline or Technogarden", private communication based an unpublished draft paper.

Hydrogen Mirror, 1998: Iceland decides to convert transport sector to hydrogen. March 1998.

MA (Millennium Ecosystem Assessment), 2005: *Ecosystems and Human Well-Being: Scenarios,* Vol. II, Island Press, Washington, DC, USA.

Marchetti, C., 1985: Nuclear Plants and Nuclear Niches, *Nuclear Science and Engineering,* 90*, 521-526.*

Morita, T., J. Robinson, *et al.* 2001: Greenhouse Gas Emission Mitigation Scenarios and Implications. *Climate Change 2001 - Mitigation.* Report of Working Group III of the Intergovernmental Panel on Climate Change. B. Metz, O. Davidson, R. Swart, and J. Pan. Cambridge, Cambridge University Press**:** 115-166.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A. *et al.* 2000: *Special Report on Emissions Scenarios* (SRES). Working Group III of the Intergovernmental Panel on Climate Change (IPCC), 595 pp. Cambridge: Cambridge University Press. Available a **http://www.grida.no/climate/ipcc/emission/index.htm**.

Nakicenovic, N., J. McGlade, S. Ma, J. Alcamo, E. Bennett, W. Cramer, J. Robinson, F. L. Toth, and M. Zurek, 2005: Lessons Learned for Scenario Analysis, *in* Carpenter**,** R. S., P. L. Pingali, E. M. Bennett, M. B. Zurek (eds.) 2005: Ecosystems and Human Well-Being, Scenarios, Volume 2, Findings of the Scenario Working Group, Millennium Ecosystems Assessment, Island Press, Washington DC, USA.

NAE (National Academy of Engineering) Board on Energy and Environmental Systems, 2004: *The Hydrogen Economy: Opportunities, Barriers and R&D Needs,* NAE Press, Washington DC.

Overbye, T. J., C. Starr, P. M. Grant, T.R. Scheider, 2002: National Energy Supergrid Workshop Report, Crowne Plaza Cabana Palo Alto Hotel, Palo Alto, California, November 6-8, 2002.

O'Neill, B. *et al.,* 2001: Population and Climate Change. Cambridge University Press, Cambridge

Rifkin, J., 2002: *The Hydrogen Economy.* Putnam, New York

Robinson, J. and P. Timmerman, 1993: Myths, rules, artifacts, ecosystems: framing the human dimensions of global change. In: *Human Ecology: Crossing Boundaries,* T. D. S. Wright, R. Borden, G. Young and G. Guagnano. The Society for Human Ecology, Colorado, pp. 236-246.

Raskin, P., G. Gallopin, A. Hammond, and R. Swart, 1998: *Bending the Curve: Toward Global Sustainability, A Report of the Global Scenario Group.* Stockholm, Stockholm Environment Institute.

Rayner, S. and E. Malone, 1988: The challenge of climate change to the social sciences. In: *Human Choice and Climate Change, Volume 4 - What Have We Learned.* S. Rayner and E. Malone. Battelle Press, Columbus, OH.

Schafer, A. and D. Victor, 1999: Global passenger travel: implications for carbon dioxide emissions. *Energy* **24**, 657679.

Schwartz, P., 1992: *The Art of the Long View*. London, Century Business.

Swart, R. *et al.*, 2004: The problem of the future: sustainability science and scenario analysis. *Global Environmental Change* **14**, 137-146.

Steffen, W., M. O. Andreae, B. Bolin, P. J. Crutzen, P. Cox, U. Cubasch, H. Held, N. Nakićenović *et al.*, 2004a: Abrupt changes: the Achilles heels of the earth system. *Environment*, **46**(3), 8-20. (ISSN 0013-9157)

Steffen, W., W., M. O. Andreae, B. Bolin, P. J. Crutzen, P. Cox, U. Cubasch, H. Held, N. Nakićenović *et al.*, 2004b: "Earth System Dynamics in the Anthropocene," inH.-J. Schellnhuber, P. J. Crutzen, W. C. Clark, M. Claussen, and H. Held, eds., *Earth System Analysis for Sustainability, Dahlem Workshop Report 91,* Cambridge, MA: The MIT Press.

Turton, H. and L. Barreto, 2004: Cars, Hydrogen and Climate Change: A Long-Term Analysis with the ERIS Model. Paper Presented to the 6th IAEE European Conference 2004 “Modelling in Energy Economics and Policy”. 2-3 September, 2004, Zürich, Switzerland.

UNFCCC (United Nations Convention on Climate Change, 1992: UNFCCC Secretariat, Bonn, Germany.

Wack, P., 1985a: Scenarios: uncharted waters ahead. *Harvard Business Review,* **5**(Sept./Oct. 1985), 72-89.

Wack, P., 1985b: Scenarios: shooting the rapids. *Harvard Business Review*, **6**(Nov./Dec. 1985), 139-150.

Appendix Ia: Overview of main scenario driving forces in 2020, 2050 and 2100. Numbers show the range across the seven scenario groups that constitute the four families. Units are given in the table. Source: Nakicenovic *et al.*, 2000.

		A1				**A2**	**B1**	**B2**
	1990	**A1C**	**A1G**	**A1**	**A1T**			
Population (billion)	5.3							
2020		7.4-7.6	7.4-7.6	7.2-7.6	7.4-7.6	7.5-8.2	7.4-7.6	7.6-7.8
2050		8.7	8.7	8.3-8.7	8.7	9.7-11.3	8.6-8.7	9.3-9.8
2100		7.0-7.1	7.0-7.1	7.0-7.7	7.0	12.0-15.1	6.9-7.1	10.3-10.4
World GDP (10^{12} 1990US$)	21							
2020		53-57	53-57	48-61	52-57	38-45	46-57	41-51
2050		163-187	164-187	120-181	177-187	59-111	110-166	76-111
2100		522-550	525-550	340-536	519-550	197-249	328-350	199-255
Income ratio IND (Annex-I) to DEV (Non-Annex-I)	16.1							
2020		6.2-7.5	6.2-7.5	5.2-9.2	5.7-6.4	9.0-12.3	5.3-10.7	7.5-12.1
2050		2.8	2.8	2.4-4.0	2.4-2.8	5.2-8.2	2.7-4.9	3.7-7.5
2100		1.5-1.6	1.5-1.6	1.5-1.7	1.6-1.7	2.7-6.3	1.4-1.9	2.0-3.6
Final energy intensity (10^6J/US$)[a]	16.7							
2020		8.8-9.3	8.5-9.4	8.1-12.0	7.6-8.7	9.3-12.4	6.7-11.6	8.5-11.8
2050		5.4-5.5	5.5-6.3	4.4-7.2	4.2-4.8	7.0-9.5	3.5-6.0	6.0-8.1
2100		2.6-3.2	3.0-3.2	1.6-3.3	1.8-2.3	4.4-7.3	1.4-2.7	3.7-4.6
Primary energy (10^{18} J)[a]	351							
2020		653-659	631-669	573-875	513-649	485-628	438-774	506-633
2050		1307-1384	1289-1495	968-1611	913-1213	679-1059	642-1090	679-966
2100		1988-2325	2059-2737	1002-2683	1255-2021	1304-1964	514-1157	846-1625
Share of coal in primary energy (%)[a]	24							
2020		29-41	24-29	8-28	8-23	18-32	8-27	14-31
2050		34-56	13-33	3-42	2-12	24-47	2-37	10-49
2100		44-48	3-29	2-41	1-2	17-53	0-22	12-53
Share of zero carbon in primary energy (%)[a]	18							
2020		13-19	12-20	9-26	17-22	8-20	7-22	7-18
2050		22-31	19-27	21-40	39-47	14-29	18-40	15-30
2100		42-47	31-38	27-75	64-85	28-37	33-70	22-50

[a] 1990 values include non-commercial energy consistent with IPCC WGII SAR (Energy Primer) but with SRES accounting conventions. Note, that ASF, MiniCAM, and IMAGE scenarios do not consider non-commercial renewable energy. Hence, these scenarios report lower energy use.

Appendix Ib: Overview of GHG, SO_2 and ozone precursors emissions (standardized) in 2020, 2050 and 2100 and cumulative CO_2 emissions from 1990 to 2100 broken down into energy and land-use sources. Numbers show the range across the seven scenario groups that constitute the four families. Units are given in the table. Source: Nakicenovic *et al.*, 2000.

		A1				**A2**	**B1**	**B2**
	1990	**A1C**	**A1G**	**A1**	**A1T**			
Carbon dioxide, fossil fuels (GtC)	6.0							
2020		11.0-14.3	10.7-13.1	8.7-14.7	8.4-10.0	7.9-11.3	7.8-13.2	8.5-11.5
2050		20.6-26.8	21.4-25.6	12.7-25.7	10.8-12.3	10.5-18.1	8.5-17.5	11.2-16.4
2100		27.7-36.8	30.3-30.8	12.9-18.4	4.3-9.1	17.6-33.4	3.3-13.2	9.3-23.1
Carbon dioxide, land use (GtC)	1.1							
2020		0.3-1.8	0.3-1.8	-0.8-1.6	0.3-1.7	0.1-3.0	-1.2-1.3	0.0-1.9
2050		0.0-0.9	0.0-0.8	0.0-1.0	-0.2-0.5	0.6-0.9	-0.7-0.8	-0.2-1.2
2100		-1.8-0.0	-2.1-0.0	-2.4-2.2	0.0-0.1	-0.1-2.0	-2.8-0.1	-1.7-1.5
Cumulative carbon dioxide, fossil fuels (GtC)	6.0							
1990-2100		2079-2478	2128-2289	1220-1989	989-1051	1303-1860	794-1306	1033-1627
Cumulative carbon dioxide, land use (GtC)	1.1							
1990-2100		31-69	31-61	31-84	31-62	49-181	-22-84	4-153
Cumulative carbon dioxide, total (GtC)	7.1							
1990-2100		2127-2538	2178-2345	1301-2073	1049-1113	1352-1938	772-1390	1164-1686
Sulfur dioxide, (MtS)	70.9							
2020		88-134	60-101	62-117	60-101	66-105	52-112	48-101
2050		72-139	64-81	47-120	40-64	78-141	29-69	42-107
2100		27-83	27-41	26-71	20-27	60-93	11-25	33-48
Methane, ($MtCH_4$)	310							
2020		415-479	416-471	400-444	415-466	354-493	377-430	384-469
2050		568-636	511-630	452-636	492-500	402-671	359-546	482-536
2100		392-693	289-735	289-640	274-291	549-1069	236-579	465-613
Nitrous Oxide, (MTN_2O-N)	6.7							
2020		6.1-9.3	6.1-9.3	6.1-9.6	6.1-7.8	6.3-12.2	5.8-9.5	6.1-11.5
2050		6.3-14.4	6.4-14.5	6.3-14.3	6.1-6.7	6.8-13.9	5.6-14.8	6.3-13.2
2100		6.1-16.2	5.9-16.6	5.8-17.2	4.8-5.4	8.1-19.3	5.3-20.2	6.9-18.1