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Interim Report **IR-04-010**

The extended energy-systems ERIS model: An overview

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Contents

Abstract

This report describes the extensions to the "bottom-up" energy-systems ERIS (Energy Research and Investment Strategies) model carried out by the authors at IIASA-ECS for, among others, the EC-sponsored SAPIENTIA and MINIMA-SUD projects. The original version of the ERIS model was developed as a joint effort between the Environmentally Compatible Energy Strategies (ECS) project at IIASA and the Energy Economics Group of the Paul Scherrer Institute (PSI) in Switzerland during the EC-sponsored TEEM and SAPIENT projects, in which it was mainly used to examine issues related to the endogenization of mechanisms of technological change. The extensions to the ERIS model developed at IIASA-ECS include: the implementation of a clusters approach to technology learning, the inclusion of emissions and marginal abatement curves for two main non-CO_2 greenhouse gases (methane (CH_4) and nitrous oxide (N_2O)), the inclusion of sulfur dioxide (SO_2) emissions, the incorporation of a transportation sector with emphasis on the passenger car sub-sector, the inclusion of fuel production technologies (e.g. hydrogen, alcohols, Fischer-Tropsch liquids, etc) as well as geological and terrestrial CO_2 storage and a calibration to the year 2000 energy statistics.

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The extended energy-systems ERIS model: An overview

1 Introduction

Defining and measuring sustainable development indicators and identifying instruments that could promote sustainability in different domains has become an important task for a number of social actors at the regional, national and international levels (e.g. Parris and Kates, 2003). Energy is one important element of sustainability. Driving the global energy system into a sustainable path is progressively becoming a major concern and policy objective (IEA, 2001; Schrattenholzer *et al.*, 2004). The emergence of a sustainable global energy system, however, is a gradual long-term process that will require a profound transformation of its current structure.

Energy-technology research and development (R&D) and demonstration and deployment (hereon referred to as D&D) programs are important driving forces in the development of energy systems (e.g. PCAST, 1999). Understanding the mechanisms by which R&D and D&D contribute to energy-technology improvements and examining their role and effectiveness in the achievement of sustainability goals in the global energy system are important tasks. Shedding light into these questions could provide policy makers with insights as to the most effective energy-related R&D and D&D strategies and complementary instruments and their potential impact on sustainability.

The SAPIENTIA project[1], sponsored by the European Commission (DG Research) examines the effectiveness of energy-technology R&D activities and demonstration and deployment (D&D) programs in stimulating technology diffusion as well as their impacts on a number of sustainability indicators in the areas of climate change, air pollution, transportation, security of energy supply and economic impacts, all topics of concern for policy makers.

An important part of the efforts in SAPIENTIA concerns the development and extension of energy-systems models such that, on the one hand, they incorporate a range of relevant key energy technologies candidate for R&D and D&D support and, on the other hand, provide an adequate representation of key mechanisms of technological change in energy systems and are able to compute sustainability indicators of interest. In addition, those models should be suitable for long-term analyses.

ERIS (Energy Research and Investment Strategies) is a multi-regional "bottom-up" energy-systems optimization model that endogenizes learning curves. The original version of the model was developed as a joint effort between IIASA-ECS and the Paul Scherrer Institute (PSI) in Switzerland during the EC-sponsored TEEM and SAPIENT projects, where it was mainly used to examine issues related to the endogenization of mechanisms of technological change (Messner, 1998; Kypreos *et al.*, 2000; Barreto and Kypreos, 2000, 2003, see also Barreto and Klaassen, 2004).

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[1] SAPIENTIA stands for Systems Analysis for Progress and Innovation in Energy Technologies for Integrated Assessment.

More recently, the ERIS model has been substantially expanded and recalibrated at ECS/IIASA by the authors in order to address the impact of alternative policy instruments on energy technology diffusion and on a wide range of sustainable development indicators related, among others, to climate change, security of energy supply and transportation. For this purpose, the model has been restructured and a number of features have been added. The main modifications include:

- development of cluster approach to technological learning;
- disaggregation and additional technological detail in the non-electric sector, particularly transportation;
- addition of an energy carrier production sector, specifically for hydrogen, alcohol and Fischer-Tropsch liquids production;
- incorporation of methane and nitrous oxide emissions and abatement cost curves for these gases;
- inclusion of sulfur dioxide emissions; and
- inclusion of geological and terrestrial carbon storage.

This report describes these changes and extensions. In addition, this report discusses the construction of the scenario used for the SAPIENTIA project and relevant characteristics of the ERIS model.[2]

2 Scenario and Model Structure

2.1 Scenario

For the SAPIENTIA project, we have constructed a “middle-of-the road” scenario. For such purpose we have collected data and assumptions from a number of sources as will be described below. Electric and non-electric demands in each world region have been taken from the B2 scenario quantified with the MESSAGE model for the IPCC Special Report on Emission Scenarios (Riahi and Roehrl, 2000; SRES, 2000).[3] However, it is not intended to reproduce or emulate any of the results of the SRES quantification here. Neither is it claimed that a consistent characterization of the SRES-B2 storyline is provided with the ERIS model.

2.1.1 Population and economic projections

The projections of economic growth and population underlying the B2 scenario have also been used in ERIS, in particular as an input to the projections of passenger car mobility developed for this analysis (on the basis of Schafer and Victor (2000), and described in more detail in Section 4.4 and Appendix A).

B2 is a “dynamics-as-usual” scenario, where differences in the economic growth across regions are gradually reduced and concerns for environmental and social sustainability at the local and regional levels rise gradually along the time horizon. Economic growth is gradual. Gross world product increases at an average rate of 2.2% per annum between 1990 and 2100. It grows from 20.9 trillion US(1990)$ in 1990 to 235 trillion in 2100 (at market exchange rates). Income per capita grows at a global average of 1.6% per year for

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[2] This report is an extended version of Turton and Barreto (2003), delivered to SAPIENTIA.

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

the same period reaching an average value of US(1990)$22,600 in the year 2100 (at market exchange rates). A process of gradual convergence between developing and developed regions progresses along the time horizon.

The population trajectory underlying this scenario is the United Nations median projection (UN, 1998), where, in the long term, global fertility levels gradually approach replacement levels. World population increases to 10.4 billion people in 2100 (9.1 billion in today's developing countries and 1.3 billion in today's industrialized ones) in a continuation of historical trends.

2.1.2 Fossil resources

Assumptions on the fossil-fuel resource base rely on the estimates of Rogner (1997) and are also made consistent with the assumptions of the B2 scenario mentioned above. Rogner's (1997) categorization distinguishes between conventional and unconventional reserves and resources and reflects increasing degrees of geological uncertainty and decreasing degrees of economic attractiveness. A relatively large availability of oil and gas is assumed. The oil and natural gas resource base comprises both conventional resources and potential for their enhanced recovery plus unconventional recoverable resources. Following Rogner's (1997) notation, categories I to VI have been considered for gas and categories I-V for oil. Categories I to III represent conventional reserves and resources. Category IV represents the potential for enhanced recovery of the conventional resources. Category V corresponds to the identified reserves of unconventional recoverable oil and gas. Category VI corresponds to the unconventional gas resource estimates.

Coal resources are also based on Rogner (1997) and are considered globally abundant, although they can be limited in some regions. Following Rogner (1997), categories A to E for both hard coal and brown coal have been considered. Category A represents proved recoverable reserves. Category B represents additional recoverable resources. Category C represents additional identified reserves while Categories D and E group together additional resources.

Table 1 reproduces Rogner's (1997) global fossil resource estimates. The resource categories used in ERIS in this scenario are shaded.

Table 1: Categories of conventional and unconventional oil, gas and coal reserves, resources and additional occurrences, in zetajoules (10^{21} J). The resource categories used in ERIS are shaded.

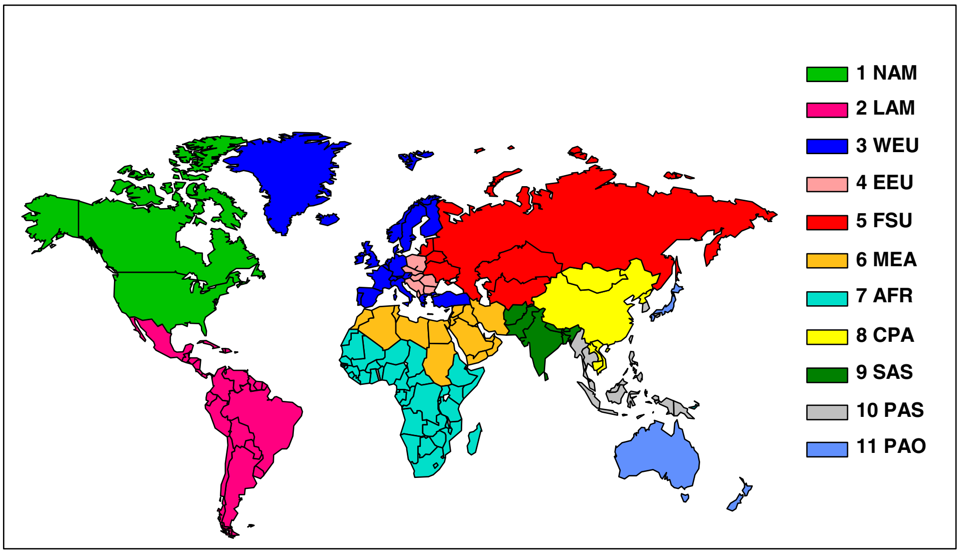
	Conventional reserves and resources	Unconventional reserves and resources			Unconventional and additional occurrences	
Category	I, II, III	IV	V	VI	VII-VIII	Total
Oil	12.4	5.8	1.9	14.1	60	94
Gas	16.5	2.3	5.8	10.8	802	837
	Proved recoverable reserves	Additional recoverable resources	Additional identified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

2.2 Model structure

2.2.1 *Regional disaggregation and time horizon*

The ERIS model has been extended to include eleven world regions, following the MESSAGE model's regional structure (Messner and Strubegger, 1995). Figure 1 shows the regional structure. Five regions portray the so-called industrialized regions and the economies in transition: North America (NAM), Western Europe and Turkey (WEU), Pacific OECD (PAO), the Former Soviet Union (FSU) and Eastern Europe (EEU). Six additional regions represent the developing world: Centrally Planned Asia (CPA), South East Asia (SAS), Other Pacific Asia (PAS), Latin America (LAM), South-Saharan Africa (AFR) and the Middle East (MEA).

The model allows interregional trade of several energy carriers (coal, oil, natural gas and hydrogen) and greenhouse gas (GHG) emissions permits. The model covers the time horizon 2000-2100 with 10-year time steps and, unless specified otherwise, a 5% discount rate is applied for all calculations.



1 NAM North America
2 LAM Latin America & The Caribbean
3 WEU Western Europe
4 EEU Central & Eastern Europe
5 FSU Former Soviet Union
6 MEA Middle East & North Africa
7 AFR Sub-Saharan Africa
8 CPA Centrally Planned Asia & China
9 SAS South Asia
10 PAS Other Pacific Asia
11 PAO Pacific OECD

Figure 1: World regions in the ERIS model, following the regional structure of the MESSAGE model. Five regions portray the so-called industrialized regions and the economies in transition (NAM, WEU, PAO, FSU, EEU). Six additional regions represent the developing world (CPA, SAS, PAS), LAM, AFR, MEA).

2.2.2 *Energy system*

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

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

The reference energy system for the current version of ERIS is presented in Figure 2. The figure shows primary fuels, conversion sectors and final demand sectors. Boxes represent primary fuels, groups of technologies and demand sectors. Figure 2 also shows the connections linking fuels with technologies and demand activities, and distinguishes flows of fuels used for secondary energy production (plain lines) and for final demand (dashed lines). To simplify the diagram, vertical parallel bars are used to group together multiple fuels or energy carriers used by one group of technologies.

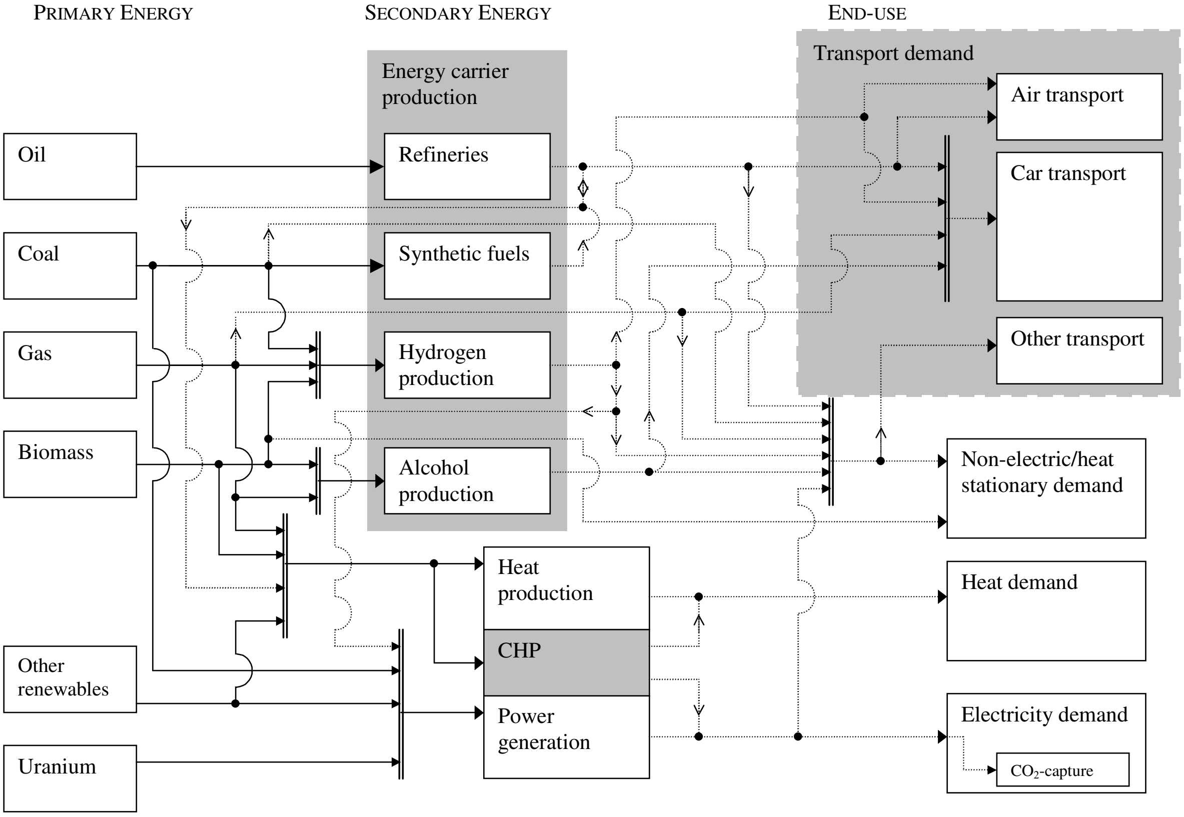


Figure 2: ERIS reference energy system. The figure shows primary fuels, conversion sectors and final demand sectors. Boxes represent primary fuels, groups of technologies and demand sectors. The connections linking fuels with technologies and demand activities are shown and flows of fuels used for secondary energy production (plain lines) and for final demand (dashed lines) are distinguished. Vertical parallel bars are used to group together multiple fuels or energy carriers used by one group of technologies.

2.2.3 Technology learning in ERIS

Technology learning is an important mechanism of technological change in energy systems (see e.g., Nakićenović, 1997).[4] The endogenization of technology learning in the models allows reflecting the fact that some technologies experience declining costs as a result of their increasing adoption (e.g., through D&D programs) in the marketplace and/or of R&D efforts. This enables an adequate representation of the causal chain between alternative policy instruments and the technology uptake in the model and the subsequent calculation of the impact of those instruments and technology diffusion on a wide range of sustainability indicators, in the areas of climate change, security of energy supply and transportation, among others.

The ERIS model allows considering both standard one-factor learning curves (hereon referred to as 1FLC), where cumulative installed capacity is used as a proxy for accumulated experience (Kypreos *et al.,* 2000) and two-factor learning curves (hereon referred to as 2FLC), where cumulative capacity and a knowledge stock function are used to represent market experience (learning-by-doing) and knowledge accumulated through R&D activities (learning-by-searching), respectively (Barreto and Kypreos, 2003).

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

$$SC(CC) = a * CC^{-b}$$

Where:

CC: Cumulative capacity
b: Learning index
a: Specific cost at unit cumulative capacity

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

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

For instance, a LR of 10% means that the costs are reduced in 10% for each cumulative capacity doubling.

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[4] Learning, or experience, effects refer to the improvements in performance in a given activity brought by experience. The learning curve reflects the fact that some technologies may experience declining costs as a result of increasing adoption into the society, due to the accumulation of knowledge by, among others, learning-by-doing, learning-by-searching, learning-by-using and learning-by-interacting processes. For a discussion of learning curves see e.g. Argote and Epple (1990), IEA (2000) or McDonald and Schrattenholzer (2002), the later two in the context of energy technologies.

For the 1FLC representation, a piece-wise linear approximation of the learning curve is obtained through Mixed Integer Programming (MIP) techniques. The MIP approach provides a linearization of the original non-linear, non-convex problem and allows identifying an optimum for the approximated problem, although at a higher computational cost. For a description of the MIP approach in ERIS see Barreto (2001) or Kypreos *et al.* (2000).

The two-factor learning curve is an extension of the standard learning curve, which is based on the hypothesis that cumulative capacity and cumulative R&D expenditures drive the cost reductions of the technology. In such 2FLC formulation, the specific cost of a given technology is a function of cumulative capacity and cumulative R&D expenditures. Such function is assumed to be of the same kind of a Cobb-Douglas production function, with both factors acting as substitutes according to their corresponding so-called learning-by-doing and learning-by-searching elasticities (Kouvaritakis *et al.*, 2000a,b).

A modified version of the two-factor learning curve, which incorporates the concept of knowledge stock (Watanabe, 1995, 1999) instead of cumulative R&D expenditures, is implemented in ERIS. Such two-factor learning curve for the specific investment costs of a given technology can be expressed as:

$$SC_{te,t} = a * C_{te,t}{}^{-b} * KS_{te,t}{}^{-c}$$

Where:

$C_{te,t}$:	Cumulative capacity
$KS_{te,t}$:	Knowledge stock
b:	Learning by doing index
c:	Learning by searching index
a:	Specific cost at unit cumulative capacity and unit knowledge stock

Instead of the learning-by-doing and learning-by-searching indexes, corresponding learning-by-doing (LDR) and learning-by-searching (LSR) rates can be defined as follows:

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

$$LSR = 1 - 2^{-c}$$

It must be noticed that the LDR does not correspond to the LR described above for the single-factor learning curve. In the 2FLC, two variables, namely the cumulative capacity and the knowledge stock are used to explicate the cost trend that the 1FLC tries to capture using only cumulative capacity as explanatory variable.

The 2FLC is formulated as a non-linear program (NLP), which is non-convex. For such problems, conventional NLP solvers are able to find only locally optimal solutions and global optimization algorithms are suitable only for very small scale problems (see e.g. Manne and Barreto, 2001).

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

2.3 Calibration of the model to the year 2000

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

3 Development of Cluster Approach to Technologies

The ERIS model was previously specified with a number of learning technologies that were identical to the energy conversion or end-use technologies. For example, advanced coal generation (IGCC) was both an electricity generation technology and a learning technology, with capacity investment costs declining as a function of installed capacity (learning-by-doing) and R&D (learning-by-searching). Consequently, each energy conversion or end-use technology learned independently, even though some had components common with other technologies and would be expected to benefit from learning in those other technologies.

To address this drawback, the ERIS model has been restructured to include clusters of learning technologies. The idea of technology clusters has been applied in several modeling approaches (Gritsevskyi and Nakićenović, 2000; Seebregts *et al.,* 2000). It is based on the fact that a technology does not evolve alone but in interaction with other technologies, infrastructures, institutions, networks of actors. etc. This “technological proximity” may stimulate a collective co-evolution process. Technological clusters are shaped when related technologies interact and cross-enhance each other, contributing to their mutual development (Nakićenović, 1997). As part of the clustering process, spillovers of learning between technologies can occur, as related or complementary technologies benefit from the learning processes of each other (Grübler *et al.,* 1999; Gritsevskyi and Nakićenović, 2000).

Following Seebregts *et al.* (2000), we have used the concept of a “key technology” to represent technology clusters in ERIS. A “key technology” is defined as one that is a component of several other technologies specified in the Reference Energy System (RES) (see Figure 2 above) – for example, the gas turbine is a key technology used in integrated gasification combined cycle (IGCC) coal, gas combined-cycle and single-cycle gas turbine electricity generation. For each key technology (hereafter referred to as a component), a learning curve is specified in ERIS. The technologies that use this component are then grouped in a cluster in such a way that installation of any one of the technologies in the cluster results in learning-by-doing in the common component, benefiting all technologies in the cluster.

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

Another benefit of applying this clustering approach to the ERIS model is that it rationalizes the number of learning technologies, allowing an expansion to a more realistic number of technologies able to improve through learning, without significantly increasing solution times.

3.1 The learning components

The learning components incorporated into the ERIS model comprise:

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

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

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

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

Table 2 presents the relationship between the technologies and key learning components.

Table 2: Learning components and technologies. Shading indicates a learning technology, and a cross indicates membership of the cluster corresponding to the component in the column heading.

Technologies			Learning components										
			FC	SFC	GT	GA	SR	AN	AP	AW	HY	CA	AG
			fuel cell	stationary fuel cell	gas turbine	gasifier	steam or autothermal reformer	advanced nuclear	PV plants	wind turbines	hybrid battery system	absorption and stripping (SELEXOL)	gas non-electric
Electricity generation	HCC	Conventional coal											
	HCA	Advanced coal			×	×							
	OLC	Conventional oil											
	GCC	NG combined cycle			×								
	GSC	Gas steam cycle											
	GTR	Gas turbine			×								
	GFC	Gas fuel cell	×	×			×						
	BIP	Biomass power plant											
	NUC	Nuclear conventional											
	NNU	New nuclear						×					
	HYD	Hydro											
	STH	Solar thermal											
	STC	Solar thermal cogen											
	SPV	Solar PV							×				
	WND	Wind								×			
	ORE	Other renewables (geothermal etc.)											
	HEF	Hydrogen fuel cell	×	×									
Non-electric stationary	GASNE	Gas non-electric											×
	COALNE	Coal non-electric											
	OILNE	Oil non-electric											
	BIONE	Biomass non-electric											
	SALNE	Alcohol non-electric											
	SH2NE	Hydrogen non-electric											
Heat techs	COALDHN	Coal district heating											
	GASDHNE	Gas district heating											
	OILDHNE	Oil district heating											
	BIODHNE	Biomass district heating											
	STHDHNE	Solar thermal heating											
	OREDHNE	Geothermal heating											
Fuel synthesis	OILREF	Conventional oil refining											
	SYNFNE	Fisher-Tropsch from coal				×							
	BIOALNE	Alcohol from biomass				×							
	GASALNE	Alcohol from gas					×						
	GASH2NE	Hydrogen from gas					×						
	COALH2N	Hydrogen from coal				×							
	BIOH2NE	Hydrogen from biomass				×							
Carbon capture	HCACS	Capture from advanced coal electricity generation and F-T fuels production										×	
	HCCCS	Capture from conventional coal										×	
	GCCCS	Capture from GCC										×	
	H2CAS	Capture from hydrogen production										×	
Cars	ICC	Internal combustion conventional											
	ICG	Internal combustion gas											
	ICA	Internal combustion alcohol											
	ICH	Internal combustion hybrid									×		
	IGH	Internal combustion gas hybrid									×		
	IAH	Internal combustion alcohol hybrid									×		
	IHH	Internal combustion hydrogen hybrid									×		
	HFC	Hydrogen fuel cell	×								×		
	PFC	Petroleum fuel cell	×				×				×		
	AFC	Alcohol fuel cell	×				×				×		
Air	AIRC	Air transport conventional											
	AIRH	Air transport hydrogen											
Other transport	COALTR	Other transport - coal											
	GASTR	Other transport - gas											
	OILTR	Other transport - oil											
	ALTR	Other transport - alcohol											
	H2TR	Other transport - H2											

4 Disaggregation of End-use Sectors

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

Previously, to avoid unrealistic outcomes – such as district heating technologies supplying all the thermal needs of the industrial sector – arbitrary and somewhat unrealistic limits were placed on the shares of non-electric energy demand that the suite of non-electric end-use technologies could supply.

The new approach ensures that end-use technologies supplying a lower quality energy service (i.e., less convenient, flexible, lower thermal quality), cannot supply higher quality needs. However, it still allows higher-quality fuels (such as electricity) to provide an energy service that could be met by a lower quality fuel. The end-use technologies and the corresponding sectors are discussed briefly below.

4.1 District heating

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

4.2 Stationary energy

Demand for higher quality stationary energy can be supplied from direct combustion of coal, oil, gas, biomass, hydrogen and alcohols, and from electricity. Note that the demands used in the ERIS model already incorporate a large shift from end-use combustion of fuels towards the use of electricity. Accordingly, the model includes the on-site use of hydrogen in fuel cells to generate electricity for thermal needs, in addition to allowing the hydrogen to be combusted for direct thermal use.

4.3 Non-energy uses

ERIS did not previously account for non-energy uses because it was developed to investigate energy technologies. However, the addition to the model of emissions of, and abatement options for GHGs other than carbon dioxide (CO_2), including those associated with coal, oil and gas production, requires a complete accounting of fuel production levels. Since there is a balance between production and consumption, this necessitates that all fuel consumption activities be incorporated into the model. In the case of non-energy uses of fuels, this is done exogenously.

4.4 Transport

Transportation has become a growing concern for the policy makers, both in terms of energy consumption and polluting emissions and analytical tools are required to shed some light into possible policy and technology actions. Thus, it is naturally one of the areas where efforts on ERIS have been concentrated.

The ERIS model has been modified to include a representation of the transportation sector. This representation divides the transport sector into three sub-sectors, namely passenger cars, air transport and others. For the first two sub-sectors, a relatively detailed technology representation is possible. In the aggregate remaining sector, generic technologies are set up to mimic the final-energy consumption.

4.4.1 Passenger cars

In the case of the passenger car sub-sector, end-use demands are input to the model in terms of kilometers of travel, rather than energy. This ensures that more energy efficient engine technologies are not disadvantaged. These demands were developed using the B2 scenario (from which the other final energy demands input to ERIS have also been derived) and a modified version of the passenger transportation demand model of Schafer and Victor (2000).

The suite of end-use technologies that can meet these demands comprise three different engine technologies (the conventional internal combustion engine (ICE), the ICE-electric hybrid, and the fuel cell-battery hybrid) using four different fuels, as shown in Table 3. Information on cost and efficiency of each of the ten technology-fuel combinations has been obtained from a variety of sources. This sector is discussed in more detail in Appendix A.

Table 3: Passenger car technologies and fuels in ERIS. Three different engine technologies (the conventional internal combustion engine (ICE), the ICE-electric hybrid, and the fuel cell-battery hybrid) are considered using four different fuels (oil products, natural gas, alcohols and hydrogen).

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

4.4.2 Air transportation

Demand projections for energy used in air transportation were developed using the B2 scenario and a modified version of the transportation model of Schafer and Victor (2000), combined with an assumption that there will be an inter-regional convergence and moderate improvement in the efficiency of aircraft. It is assumed that only petroleum-based fuels and hydrogen can be used to power aircraft, although hydrogen-fuelled aircraft will not be available until 2050. If necessary, the technological detail in this sector could be increased.

4.4.3 Other transportation

The energy demands of the remaining transportation sectors (excluding electric rail) have been combined and are represented in a stylized way in the ERIS model. These demands are supplied by direct combustion of petroleum fuels, gas, coal and alcohols, and the dissociation of hydrogen in a fuel cell. Demand is given in energy units, although hydrogen is assumed to be used 50% more efficiently than the other fuels (since it is assumed to be the only fuel used in fuel cells in ‘other transportation’).

5 New Energy-carrier Production Technologies

5.1 Energy carriers

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

5.2 Fuel transmission and distribution infrastructure costs

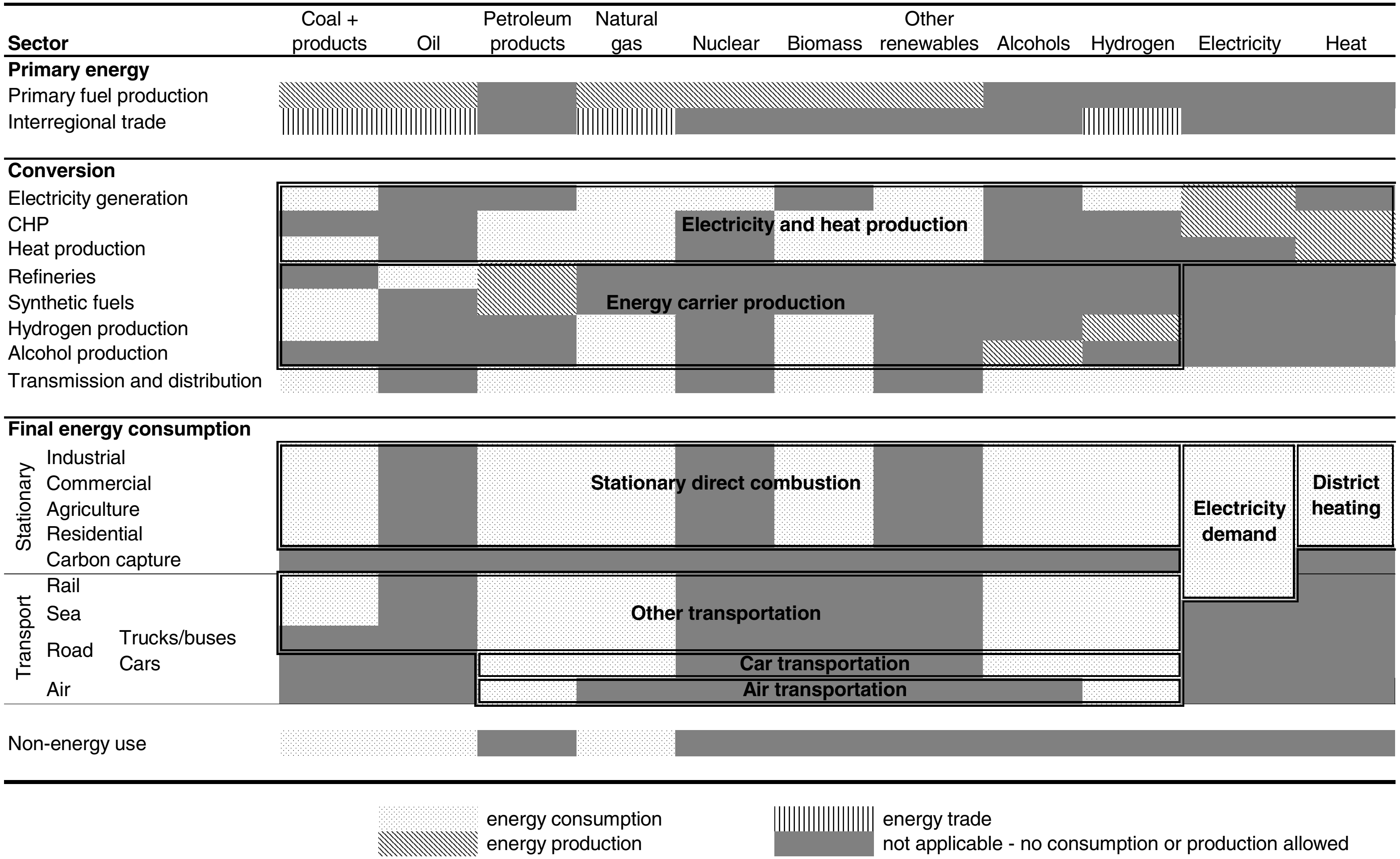
It is important to note that primary and secondary fuels (energy carriers) used by end-use sectors need to be transported to the site of final demand. The cost of the infrastructure required to transport these fuels may have a bearing on the choice of fuel for a particular application. In cases where final demand can only be met by a single fuel, transmission and distribution costs are not critical because the single fuel is distributed using the same infrastructure.

On the other hand, where different energy carriers compete to supply energy demand (such as in stationary direct fuel use or transport), the costs of distributing different fuels or energy carriers may vary widely, and this may affect the relative competitiveness of the different fuels. For example, hydrogen competes with petroleum in supplying transport energy demand, but these two fuels rely on separate delivery systems, the cost of which will affect the relative price of hydrogen and petroleum to final consumers.

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

Table 4 shows how the definitions of the demand and conversion sectors used in ERIS relate to energy balance accounting. Double-bordered boxes denote groups of technologies.

Table 4: Sectoral disaggregation in the ERIS model. The table shows how the definitions of the demand and conversion sectors used in ERIS relate to energy balance accounting. Double-bordered boxes denote groups of technologies.



Sector			Coal + products	Oil	Petroleum products	Natural gas	Nuclear	Biomass	Other renewables	Alcohols	Hydrogen	Electricity	Heat
Primary energy													
Primary fuel production			▨	▨	■	▨	▨	▨	▨	■	■	■	■
Interregional trade			▥	▥	■	▥	■	■	■	■	▥	■	■
Conversion													
Electricity generation			░	■	■	░	░	■	░	■	░	▨	■
CHP			■	■	░	░	░ **Electricity**	░ **and heat production**	░	■	■	▨	▨
Heat production			░	■	░	░	■	░	░	■	■	■	▨
Refineries			■	░	▨	■	■	■	■	■	■	■	■
Synthetic fuels			░	■	▨	■ **Energy**	■ **carrier production**	■	■	■	■	■	■
Hydrogen production			░	■	■	░	■	░	■	■	▨	■	■
Alcohol production			■	■	■	░	■	░	■	▨	■	■	■
Transmission and distribution			░	■	░	░	■	░	■	░	░	░	░
Final energy consumption													
Stationary	Industrial		░	■	░	░	■	░	■	░	░	░	░
	Commercial		░	■	░	░ **Stationary direct**	■ **combustion**	░	■	░	░	░	░ **District**
	Agriculture		░	■	░	░	■	░	■	░	░	░ **Electricity**	░ **heating**
	Residential		░	■	░	░	■	░	■	░	░	░ **demand**	░
	Carbon capture		■	■	■	■	■	■	■	■	■	░	■
Transport	Rail		░	■	░	░	■	■	■	░	░	░	■
	Sea		░	■	░	░ **Other**	■ **transportation**	■	■	░	░	■	■
	Road	Trucks/buses	■	■	░	░	■	■	■	░	░	■	■
		Cars	■	■	░	░	■	■ **Car transportation**	■	░	░	■	■
	Air		■	■	░	■	■	■ **Air transportation**	■	■	░	■	■
Non-energy use			░	░	■	░	■	■	■	■	■	■	■

░ energy consumption
▨ energy production
▥ energy trade
■ not applicable - no consumption or production allowed

6 Addition of Emissions and Abatement Options

The model has been extended to consider GHGs other than CO_2, namely the two main gases, methane (CH_4) and nitrous oxide (N_2O). Although CO_2 is the largest historical contributor to climate change and will most likely continue to have a very important relative role in the future, CH_4 and N_2O are the two main non-CO_2 GHGs. The atmospheric concentrations and radiative forcing of these three GHGs have been increasing as a result of human activities (IPCC, 2001b).

Our modeling framework endogenizes these three main GHGs, although we concentrate mainly on the contribution of the global energy system. The incorporation of these gases is an important addition when examining cost-effective strategies for mitigation of global climate change. Specifically, considering their abatement potentials may have noticeable effects on the costs and composition of GHG mitigation strategies. Exogenous assumptions are made for other GHGs.

Emissions of sulfur dioxide (SO_2) have also been included because oxidation of this gas produces sulfate aerosols (SO_4^{2-}) which can have a significant impact on the climate. These aerosols tend to produce a cooling effect, both directly through reflecting solar radiation into space and indirectly through their impact on clouds (Hulme *et al.,* 2000).

6.1 Methane and nitrous oxide

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

Emissions associated with the mining of coal and the extraction of oil and natural gas were linked endogenously to the production levels of each fuel in the model, based on estimates from the U.S EPA (2003) and fuel production figures from the IEA (2003a,b). The remaining non-CO_2 emissions were exogenous to the model, and extrapolated linearly to 2100.

Abatement cost curves for CH_4 and N_2O emissions from a number of sources for 2010 and 2020 were obtained from the EPA (2003).[5] These were extrapolated to 2100 for each source assuming that the proportion of emissions that can be abated for a given cost is independent of the absolute level of emissions. That is, if 20% of the emissions from landfills can be abated for US$20/ton of carbon-equivalent (tC-e)[6] in 2020, then it is assumed that 20% of the emissions from landfills in 2050 can be abated for the same cost. A representative abatement cost curve is presented in Figure 3.

Abatement cost curves were not available for a number of significant sources – notably enteric fermentation and agricultural soils – and it is conservatively assumed that there are no abatement opportunities associated with these activities.

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[5] For applications of the abatement curves see, for instance, Reilly *et al.* (1999, 2002) or De la Chesnaye *et al.* (2001).

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

In addition, CO_2 emissions from cement production were also incorporated into ERIS, as an exogenous factor linked to industrial thermal energy demand (which is itself exogenous to the model).

6.2 Sulfur dioxide emissions

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

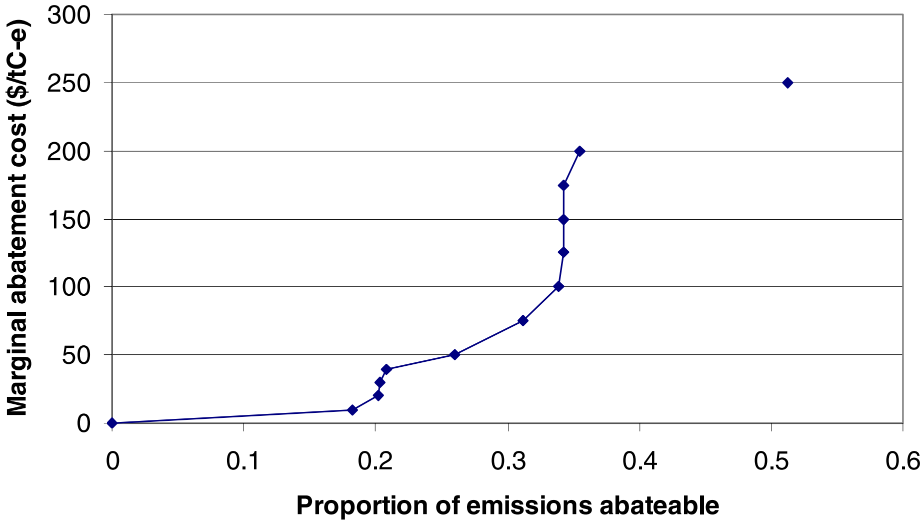

Figure 3: Marginal abatement cost (MAC) curve showing the proportion of CH_4 emissions from natural gas production abatable for different costs for Western Europe in the year 2020. Original data are from EPA (2003). Note that the most upper right data point represents the total abatement possible above US$200/tC-e. MACs for this and a number of other sources have been incorporated in the ERIS model.

7 Inclusion of Geological and Terrestrial Sequestration

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

7.1 Carbon capture, geological storage and leakage

A number of carbon capture technologies were added to ERIS to better represent abatement options. These capture technologies have been defined as add-ons to various emitting technologies and their costs (capital and operating) and energy requirements vary depending on the additional components required (see David and Herzog, 2001, and Appendix A).

ERIS allows capture of carbon from hydrogen and synthetic fuels production, conventional (steam) and advanced (IGCC) coal electricity generation, and gas combined cycle and fuel cell electricity generation.

Captured carbon is stored, with a user-defined percentage of total stored CO_2 assumed to leak each year.

7.2 Forest sequestration

The potential for and cost of sequestration in carbon sinks was derived from the TAR (IPCC, 2001a, Sections 4.3 and 4.5) and Reilly *et al.* (2002). Restrictions on the growth in carbon sinks, and limits on the total sequestration are included.

8 Linkage to the Climate MAGICC Model

Among other sustainability indicators, the SAPIENTIA project addresses climate change. There is increasing evidence of anthropogenic interference with the Earth's climate system and mounting concerns about possible serious adverse impacts of future global climate change (IPCC, 2001a,b). Thus, mitigation and adaptation to climate change constitute important aspects of a transition to sustainability in the long term.

Figure 4 presents a simplified representation of the economic-climate cause and effect chain considered here. That is, from socio-economic driving forces (in particular technological change in energy systems) to climate variables, assuming that all concentration changes act on climate change via radiative forcing. No subsequent steps in the causal chain, such as climate change impacts or damages are considered. Also, except for the impact of temperature on the terrestrial carbon cycle, a once-through chain has been assumed, with no feedbacks from climate variables to driving forces.

According to their relevance, current use in the climate change debate and measurability, the following climate change indicators have been chosen: CO_2, CH_4 and N_2O emissions, concentrations of CO_2, CH_4 and N_2O in the atmosphere, radiative forcing, annual-mean global temperature change and global-mean sea level rise. These indicators allow an aggregate but meaningful characterization of climate change at the global level and have been widely recognized and used, in particular by the IPCC (1996, 2001b). Despite their aggregate character, these indicators have a straightforward interpretation and allow an adequate examination of the effects of alternative policies on climate change at the global scale.

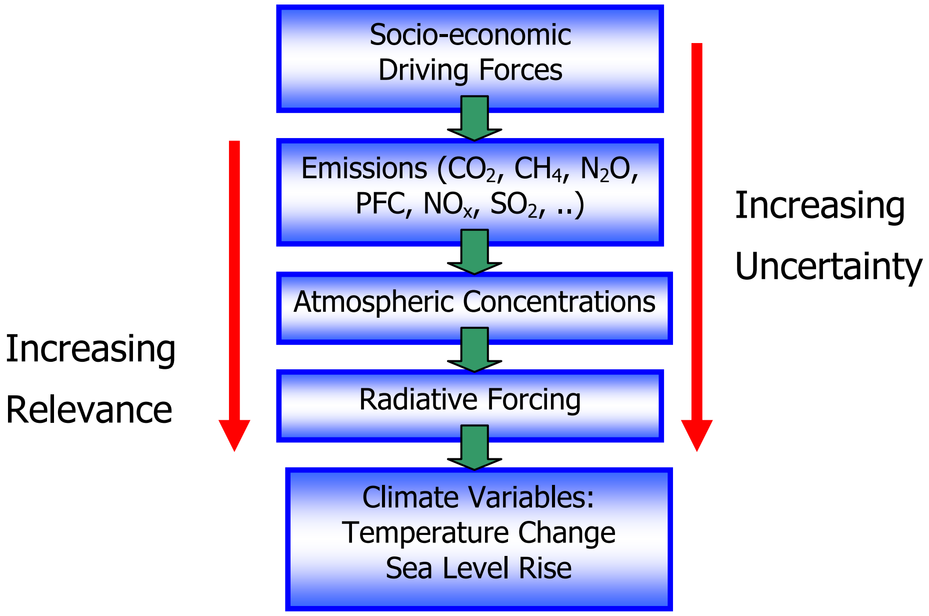

Figure 4: The cause-effect chain from driving forces to climate change considered here (adapted from IPCC, 2001b and Fuglestvedt *et al.*, 2003). It is assumed that all atmospheric concentration changes act on climate change via radiative forcing. Other than temperature feedbacks on terrestrial carbon cycle, a once-through causal chain has been assumed.

In order to estimate the indicators of climate change, the ERIS model has been linked to the stylized climate change model MAGICC (version 4.1, Wigley, 2003) developed by Wigley and Raper (1997) and also described in Hulme *et al.* (2000). MAGICC includes all the major greenhouse gases and the effects of regionalized (three world regions) fossil fuel-derived SO_2 emissions through sulfate aerosol effects.

The ERIS model generates inputs to MAGICC of energy-related CO_2 emissions (minus geosequestration), CO_2 emissions from cement production, CO_2 sequestration in forest sinks and comprehensive emissions of CH_4 and N_2O. Other emissions are exogenously specified, including emissions of halocarbons, sulfur hexafluoride (SF_6), non-N_2O oxides of nitrogen (NO_x), volatile organic compounds (VOCs) and carbon monoxide (CO), and net emissions from deforestation. Estimates of these emissions have been taken from the IPCC/SRES B2 scenario and, for the scenarios studied for the SAPIENTIA project, are assumed to be independent of energy system characteristics.

The linkage between the energy-systems ERIS model and the climate change MAGICC model is presented in Figure 5.

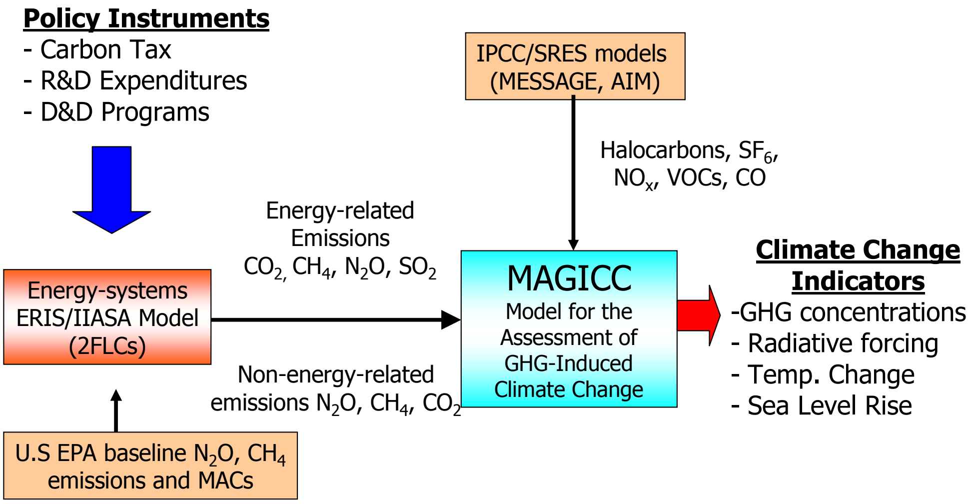

Figure 5: Linkage between the energy-systems ERIS model and the climate change MAGICC model. This model linkage allows the computation of climate change indicators of interest.

9 Incorporation of Policy Instruments

In this section, we describe the changes that were necessary in the model in order to make it suitable to examine the effects of three main policy instruments, namely R&D activities, D&D programs and carbon taxes. For the sake of comprehensiveness, a fourth instrument, emission trading, is briefly described, although this was already included in the original version of ERIS (Barreto and Kypreos, 2000; Barreto and Klaassen, 2004) and under some circumstances, its effects can be similar as those of a carbon tax.[7]

The first two instruments are related to the direct stimulation of technology learning in specific technologies or clusters of them. R&D and market experience can be thought of as two learning mechanisms that act as complementary channels for knowledge and experience accumulation. Both mechanisms play an important role. R&D is critical at early stages of development and to respond to market needs but market experience is essential to achieve competitiveness.

A comprehensive view of technological learning processes and associated policy measures must encompass Research, Development, Demonstration and Deployment activities (summarized as RD3 following PCAST, 1999), since all of them play a role in stimulating energy innovation and in the successful diffusion of emerging energy technologies.

Within the SAPIENTIA project, the effects of stimulating these two main channels of technology learning are examined using so-called R&D and D&D (or capacity) "shocks". That is, we examine the response of the model and the indicators to a small one-time incremental variation in the R&D knowledge stock or cumulative capacity of a given technology.

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[7] The carbon tax is a good generic choice for the consideration of climate-policy instruments. For instance, when examined at the global level, the effects of a carbon tax do not differ from those of global emissions trading, for the case where the emission permit price is the same as the carbon tax.

As for carbon taxes, they are contemplated as one of the policy instruments for achieving emission reduction targets and for promoting the diffusion of cleaner, low-emissions energy technologies. The taxes provide a disincentive for emitting CO_2 (they could also be extended to other GHGs) without specifying the amounts of emissions that should be reduced. They may encourage the development and deployment of technologies that make emissions reductions less costly in the long term (see e.g. Jaffe *et al.*, 2000). Carbon taxes or similar instruments have been already implemented in some countries and have been proposed at the international level, among others by the European Commission. Thus, examining the effect of carbon taxes on encouraging technological pathways that drive to a more sustainable energy system in the long run constitutes an important task.

Emission trading has been proposed as one of the flexibility instruments to comply with GHG emission reductions. It gives parties with expensive in-house mitigation options the possibility of profiting from cheaper alternatives available somewhere else by buying emission permits. Taking advantage of the “where-flexibility” of GHG mitigation, trading would contribute to achieving emissions reductions in a cost-effective way. Its effectiveness, however, has to be examined both from static and dynamic perspectives. One of the aspects of its dynamic efficiency concerns impacts on technological change.

9.1 R&D shocks in one-factor learning

The ERIS model can be formulated as an MIP problem to include one-factor learning curves, including learning-by-doing effects (Kypreos *et al.*, 2000; Barreto and Kypreos, 2000) or as an NLP to include two-factor learning – that is, learning-by-doing and learning-by-searching (Barreto and Kypreos, 2003). The two-factor learning NLP version of the ERIS model is well suited when investigating the optimal allocation of an R&D budget across a range of technologies. However, the NLP formulation of the model is a non-convex program, and conventional solvers are unable to identify the global minimum amongst several local minima, thus requiring the use of global optimization techniques, which are only suitable for small-scale problems (e.g. Manne and Barreto, 2001).

When, however the interest lies in the examination of the impact of a series of orthogonal R&D shocks, or stimuli, to a number of technologies, rather than on the optimization of an R&D budget, the NLP formulation is not convenient. To examine the impact of a single R&D shock on a particular technology, an MIP formulation of the ERIS model is used, with the learning-by-doing parameters modified according to the impact of an R&D shock. The MIP approach employed in ERIS uses stepwise interpolation along the one-factor learning formulation:

$$SC_{te,t} = a' * C_{te,t}^{-b} \tag{1}$$

Where: $SC_{te,t}$ is the specific cost of the technology; $C_{te,t}$ the cumulative capacity; a', the specific cost at unit cumulative capacity; and, b, the learning-by-doing index. In comparison, the two-factor learning curve formulation used by Barreto and Kypreos (2003) is as follows:

$$SC_{te,t} = a * C_{te,t}^{-b} * KS_{te,t}^{-c} \tag{2}$$

Where: $KS_{te,t}$ is the knowledge stock; *a*, the specific cost at unit cumulative capacity and unit knowledge stock; *b*, the learning-by-doing index; and, *c*, the learning-by-searching index. Rearranging equations (1) and (2) reveals the following relationship:

$$a' = a * KS_{te,t}^{-c} \tag{3}$$

A single shock that increases the knowledge stock (KS) leads to a decrease in a', the specific cost at unit cumulative capacity in the single-factor formulation. If the knowledge stock remains constant thereafter, then a' remains constant. Accordingly, an R&D shock can be incorporated into the single-factor learning formulation by varying a' according to Equation 3.

9.2 Capacity shocks

The existing MIP formulation is well-suited for assessing the impact of an exogenous investment in deployment and demonstration of a particular technology (referred to as a D&D shock). The installation of additional capacity:

- increases the available capacity of a particular technology, thereby increasing the aggregate capacity of all technologies and delaying the need for new capacity; and
- increases experience with the particular technology and hence, where the technology includes learning components, reduces the cost of the technology and that of others in the same cluster. That is, the addition of capacity results in a movement along the learning curve.

It should be emphasized that unlike R&D shocks, which affect a single learning *component*, capacity shocks affect an entire *technology* comprising a number of learning and non-learning components. This is a realistic treatment of technology deployment because it is not possible to deploy a single component without also installing the rest of the system necessary for its operation.

9.3 Carbon tax

A carbon tax, or more correctly carbon-equivalent tax for CO_2, CH_4 and N_2O emissions, has been incorporated into the ERIS model. The current formulation allows the user to set a constant global carbon tax across the entire period. It would be relatively simple to modify the model to allow temporal and regional variations in the carbon tax rate. In our modeling framework, it is possible to examine the response to different carbon-equivalent tax levels.

9.4 Emission trading

The multi-regional ERIS model takes emissions trading between regions into account by the following constraints:

$$EMGHG_{rg,t} + NTXGHG_{rg,t} \le IEGHG_{rg,t}$$

$$\underset{rg}{} NTXGHG_{rg,t} = 0$$

Where:

$EMGHG_{rg,t}$: GHG emissions in the region rg for the time period t (a variable).

$NTXGHG_{rg,t}$: Net export of GHG emissions from the region rg in the time period t (a variable).

$IEGHG_{rg,t}$: Initial endowments of GHG emissions for the region rg in the time period t (a parameter).

It should be clarified how the emissions trading mechanism operates in this “bottom-up” context. Emissions trading basically allows the reallocation of the carbon reduction targets and, therefore, of the incentives to deploy low-carbon technologies among the regions participating in the trade system. Carbon emissions reductions are distributed across regions such that their marginal reduction costs are equalized and the most cost-effective emission reduction options are selected. Also, since buying expenses and sales revenues of emission permits are not endogenous to the model but can only be computed ex-post, our approach cannot measure the benefits of trading, which can be particularly significant for the selling regions.

The effects of emissions trading, carbon taxes and other climate policy instruments are influenced by their interaction with the learning processes of emerging and established energy technologies. Specifically, the magnitude of spillovers of learning between different regions plays a significant role. On the one hand, the learning process will be affected by the configuration of the trading system and the level and location of the emission constraints imposed. On the other hand, the stimulation or discouragement of learning of low-carbon technologies, for instance through governmental technology and energy policies, would affect the ability of a given region to participate in the trading regime and the amounts of emissions it sells/buys (for a discussion see e.g. Barreto and Kypreos, 2004; Barreto and Klaassen, 2004).

9.5 The instrument-to-indicator causal chain

In order to be able to examine the effects of alternative policy instruments on sustainability indicators of interest, an adequate representation of the so-called instrument-to-indicator causal chain is required.

As an illustration, Figure 6 presents the instrument-to-indicator chain for climate change using the ERIS-MAGICC modeling framework. Essentially, the application of the R&D and D&D instruments can stimulate the technology learning of low-emissions energy technologies, bringing cost reductions and other performance improvements. This makes those technologies more cost-effective and attractive in the marketplace, leading to their diffusion, initially in niche markets and later in broader markets. The imposition of a carbon-equivalent tax, on the other hand, provides an incentive for the adoption of technologies with lower associated GHG emissions. As a result of the diffusion of low-emissions energy technologies, the global energy system emits a smaller amount of GHG to the atmosphere, thereby leading to lower atmospheric GHG concentrations. All other things being equal, lower GHG concentrations result in a lower radiative forcing and a smaller increase in temperature and sea level.

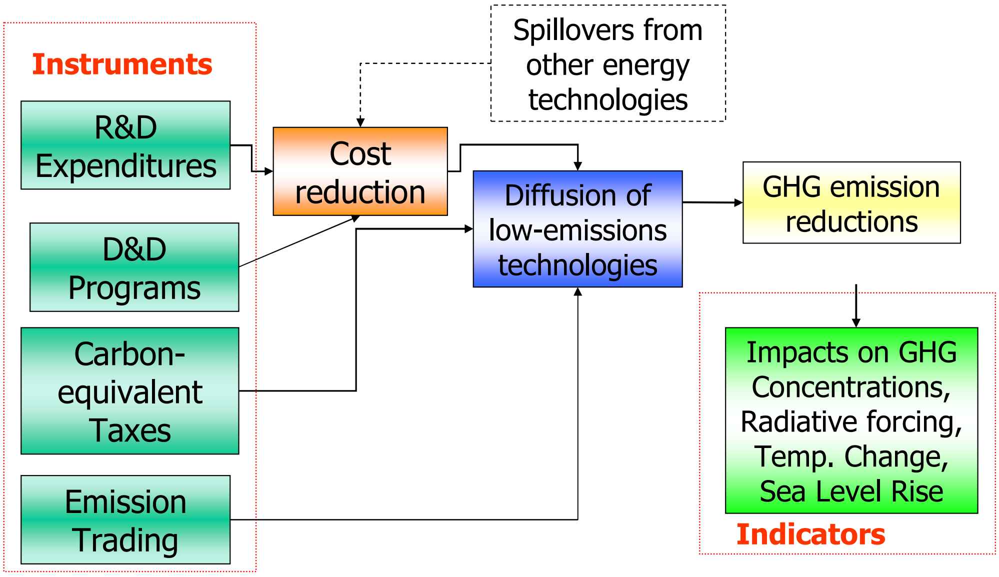

Figure 6: Instrument-to-indicator chain for climate change sustainability indicators.

10 Concluding Remarks

This report has documented the changes made to ERIS, a “bottom-up” energy-systems optimization model that endogenizes learning curves, by the authors at IIASA-ECS in order to address the objectives of the EC-sponsored SAPIENTIA project.

For this purpose, the model has been restructured and a number of features have been added. Several non-electric sectors, covering transportation and thermal needs, and corresponding technologies have been incorporated. Also, fuel production technologies have been included, specifically for hydrogen, alcohol and Fischer-Tropsch liquids production. More importantly, a clusters approach to the representation of technologies, which allows different technologies to share a common “key learning component” and accounts for the corresponding learning spillovers, has been developed. In addition, marginal abatement curves for several non-CO_2 greenhouse gases and forest sinks have been added and CO_2 capture and storage technologies are modeled.

In view of its importance to policy makers, special attention has been given to the representation of the passenger vehicle sector, such that an examination of the possible technological transitions in the car sector and its energy-supply system in the long term can be carried out and the effect of alternative policy instruments in such transitions can be assessed.

In order to be able to represent adequately the costs and composition of GHG mitigation strategies in our modeling framework, marginal abatement curves for two main non-CO_2 greenhouse gases (CH_4 and N_2O) and forest sinks have been added and CO_2 capture and storage technologies are modeled in ERIS.

In addition, and also in order to enable an adequate examination of the complex interactions between technological change in energy systems and the climate change issue, the ERIS model has been linked to MAGICC, a simplified climate model. This allows the quantification of several key global indicators of climate change and the examination of the ability of alternative policy instruments to stimulate technological pathways that drive to a low-emissions energy system in the long run.

Appendix A: Passenger car transportation demand, technologies, costs and efficiencies

A1. Estimates of demand

Vehicle occupancy, travel demand (in passenger km) and passenger vehicle shares were estimated using the model of Schafer and Victor (2000). This model projects these transport parameters to 2050 for the IS92a/e scenario (Leggett *et al.,* 1992) based on stable time and money share budgets. Because the current study is based on a different population and economic growth scenario (B2 instead of IS92a/e) and a longer timeframe (to 2100 rather than 2050), it was necessary to extrapolate some of the regressions of Schafer and Victor (2000), taking into account realistic trends in vehicle ownership, the share of various modes and likely occupancy and utilization levels.

These projections were combined with estimates of distance traveled per vehicle (Schafer, 1998) to estimate future demand for passenger vehicles. Estimates of 1990-2000 vehicle utilization rates were derived from data on vehicle numbers (AAMA, 1997, 1996; FHA, 1996; EIA, 1999; IRF, 2000) and Schafer and Victor's (2000) models of occupancy and travel demand. These trends were extrapolated based on convergence around 10-16,000 km pa (Schafer, 1995) for all regions except North America, which is assumed to converge to around 22,000 km pa.

Figure A1 presents the implied levels of passenger vehicle ownership in the scenario developed here. This figure shows three main trends: a) car ownership in developed regions peaks and begins to declines as higher incomes (and higher travel money budget) make faster modes more attractive; b) a catching-up of Eastern Europe (EEU) and the Former Soviet Union (FSU); and c) rapid growth in some developing regions – notably Pacific Asia (PAS) and Latin America (LAM). Overall future demand for passenger car travel is presented in Figure A2.

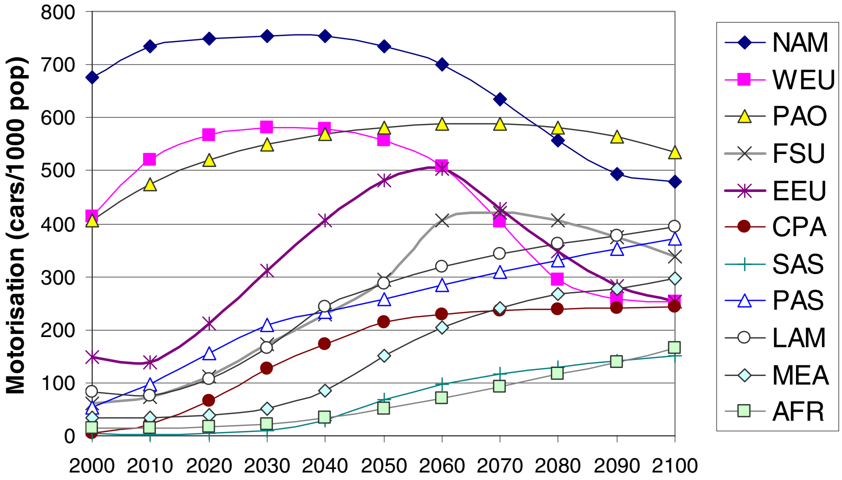

Figure A1: Projected car ownership levels, 2000-2100.

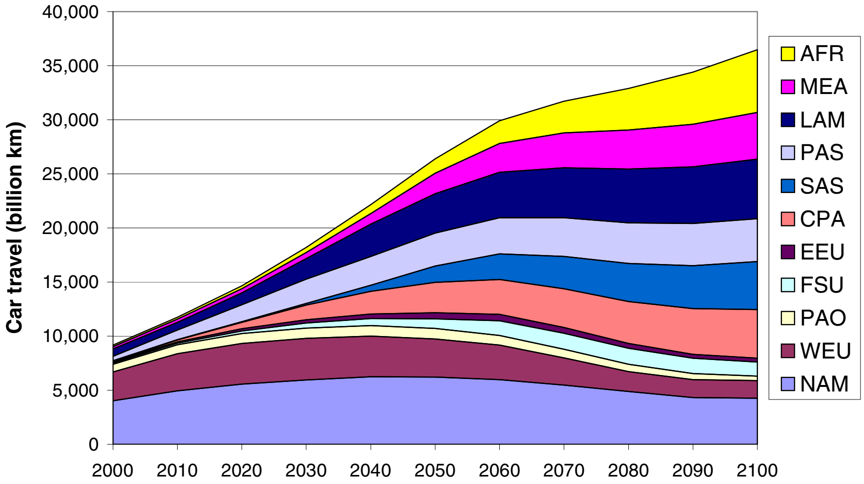

Figure A2: Projected future demand for passenger car travel. Demand in industrialized regions peaks and declines in the second half of the 21st century. Although economies-in transition demand experiences a noticeable increase but their fraction of the world total demand remains small. In developing regions, growth is much more vigorous and by the end of the 21st century they dominate the demand for passenger car travel at the global level.

The models of Schafer and Victor (2000) were also used to develop estimates of future passenger air transport that were consistent with trends in private passenger vehicle travel.

A2. Car transport efficiency

Estimates of vehicle technology drive-train fuel efficiency were derived from Weiss *et al.* (2003), Thomas *et al.* (2000), Weiss *et al.* (2000), ADL (2002) and Ogden *et al.* (2004). Regional vehicle fuel efficiencies for developed regions were obtained from Landwehr and Marie-Lilliu (2002). Fuel efficiency in developing regions, where data are unreliable or unavailable, was assumed to be roughly the average of that in the developed regions. This is probably unrealistic in the base year because in many of these regions there is a lack of adequate vehicle maintenance and poor quality roads (Michaelis, 1996). However, private passenger vehicle travel consumes a relatively small amount of energy in the base year in these regions, and any significant increase in vehicle numbers is likely to coincide with an improvement in overall vehicle fuel consumption, and convergence with developed regions (because of demand for improved roads, increased availability and competition in vehicle maintenance industry and more competition with foreign vehicle manufacturers). Accordingly, these estimates used for developing region fuel economy are likely to be reasonable over the longer term, where this form of travel becomes more significant.

The efficiency of the conventional internal combustion engine vehicle is assumed to improve at 0.2% per annum. This conservative estimate is used to reflect that improvements in vehicle weight, aerodynamics, rolling resistance, engine etc., will be offset somewhat by demand for larger vehicles with more energy-consuming onboard systems as incomes grow. The relative drive-train efficiencies are assumed to remain constant.

A3. Car technology component costs and learning

Total drive train system costs for mass-produced vehicles were derived from Ogden *et al.* (2004); Weiss *et al.* (2000), Thomas *et al.* (2000) and ADL (2002) (although the estimates in latter were somewhat higher). The derivation of the costs of the various learning components – fuel cell, reformer and hybrid battery system – used in the car transportation technologies is discussed below.

The electric hybrid system (comprising electric motor, generator and battery system) used in both the ICE-electric hybrids and the FC-battery hybrids is assumed to cost US$1600 per mass-produced vehicle, based on estimates of battery cost of around US$700 and generator and control systems of cost of US$900, consistent with a number of estimates (Ogden *et al.,* 2004; Weiss *et al.,* 2000). However, current battery costs are 2.5-4 times estimated potential (ADL, 2002). This guides the starting and floor costs for the battery system used in ICE hybrid and fuel cell hybrid vehicles.

Complete fuel cell system costs for 2001 are estimated to be US$324/kW (Carlson *et al.,* 2002) for a 50 kW PEM system. The majority of this (US$220/kW) is for the fuel cell subsystem and reformer (US$76/kW). However, these costs are expected to decline, with various sources presenting a range of estimates of likely future FC prices from US$30-60/kW, with complete direct hydrogen fuel cell system cost ranging from US$50 to $110/kW (with reformer-based petroleum and alcohol systems likely to cost an additional US$20-50/kW) (ADL, 2002; Carlson *et al.,* 2002; Ogden *et al.,* 2004; Weiss *et al.,* 2000).

A passenger motor vehicle fuel cell power output of 40 kW per has been chosen, roughly in line with estimates for a battery-hybrid fuel cell vehicle (ADL, 2002; Ogden *et al.,* 2004; Weiss *et al.,* 2003). At this output slightly higher starting costs for the fuel cell subsystem and reformer unit have been assumed (US$250/kW and US$90/kW, respectively) in line with Carlson *et al.* (2002). A mid-point in the range of future fuel cell prices is used as the floor costs for this technology.

Methanol-based steam reformers (SR) are expected to remain cheaper than the auto-thermal reformers used in gasoline fuel cell vehicles (ADL, 2002; Thomas *et al.,* 2000), and both fuel processing systems will require a more costly fuel cell to cope with the lower fuel quality. Future reformer costs range from US$10-20/kW for steam, and US$20-40/kW for auto-thermal (Ogden *et al.,* 2004), which is consistent with Thomas *et al.* (2000) and Weiss *et al.* (2000). For this analysis, we have taken a floor cost of US$25/kW for the SR and a starting cost of US$90/kW (the latter based on Carlson *et al.,* 2002).[8]

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[8] Starting and floor costs for auto-thermal reformers have been assumed to be $110/kW and $45/kW, respectively.

Appendix B: Stationary Components and Costs

B1. Electricity generation and energy carrier components

The initial costs of the various new components incorporated into the ERIS model and used in stationary electricity generation are discussed below. Some of these components, such as the gasifier and reformer, are also used in some of the energy carrier production technologies.

The stationary fuel cell (FC) system is assumed to comprise two learning components: one that is specific to stationary FC applications and another that is common to both stationary and mobile fuel cells. As a consequence, installation of a stationary FC results in some spillover benefits to mobile applications and vice versa, although there is a limit to the amount which total system costs can decline as a result of the installations of the common component. The stationary-specific FC component is assumed to cost US$1250/kW, while the common component costs US$250/kW (corresponding to the cost of the mobile FC discussed in Appendix A).[9] This approach captures learning spillovers between the stationary and mobile fuel cell technologies.

Gas turbines are assumed to cost US$200/kW (Parsons and Shelton, 2002), representing roughly 2/3^{rds} of the cost of a gas turbine generation plant. This component is used in advanced coal (IGCC), gas turbine and gas combined cycle generation.

Gasifiers, comprising air separation, oxygen compressor and gasification, are assumed to cost US$250/kW$_{th}$, which is equivalent to US$400-500/kW$_e$ for an IGCC plant (Parsons and Shelton, 2002; Hamelinck and Faaij, 2001). This component is used in advanced coal generation (IGCC), coal-to-liquids (Fischer-Tropsch) synthesis, production of hydrogen from coal and biomass and production of alcohols from biomass.

The steam reformer (combined with a Pressure Swing Absorber (PSA)) is estimated to cost US$180/kW (Simbeck and Chang, 2002; Hamelinck and Faaij, 2001), and we have assumed the same relative learning potential as for transport-based steam reformers. In stationary applications, this component is used in the gas fuel cell, and in hydrogen and alcohol production from natural gas.

B2. Carbon capture technologies

Overall costs of carbon capture technologies are based on David and Herzog (2001). The costs of the components (learning and non-learning) that make up these

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[9] To illustrate, each dollar spent on a stationary FC system has the same impact on learning-by-doing in the mobile FC of a direct investment of around 17 cents. Conversely, each dollar invested in mobile FC capacity affects learning in one-sixth of the total installation cost of a stationary FC.

technologies have been sourced from Kreutz *et al.* (2003) and Parsons and Shelton (2002) and are discussed below.

CO_2 stripping, based on the SELEXOL process, is reported to cost US\$140/kW$_e$ for an IGCC plant (Parsons and Shelton, 2002) after grossing up process costs to total plant investment. Using Parsons and Shelton's (2002) emissions factors, this translates to around US\$70 for a carbon (C) processing capacity of one ton per year. Kreutz *et al.* (2003) suggest a lower price for SELEXOL adsorption. However, they have assumed lower balance of plant, engineering, contingency and miscellaneous cost.[10]

Parsons and Shelton (2002) estimate the capital costs of the amine process for CO_2 separation from lower concentration flue gas streams. They estimate CO_2 separation costs of US\$165/tC/yr for PC generation and US\$325/tC/yr for gas. Combined with CO_2 compression and drying costs of around US\$40-50/tC/yr (Parsons and Shelton, 2002; Kreutz *et al.,* 2003), these figures are comparable to those of David and Herzog (2001).

Carbon transport and storage costs are estimated to be US\$26/tC, based on estimates of Freund *et al.* (2003). They report that a plausible range for costs of storage of CO_2 in deep saline aquifers or depleted oil/gas fields is US\$1-3/tCO_2 (US\$3.7-11/tC). Here we have adopted the mean value of this range, which corresponds to US\$7.3/t C, for our calculations. It must be recognized, however, that many uncertainties surround these figures. Also, that storage costs will depend on the particular characteristics of specific reservoirs, the rates of injection etc.

As for transportation of captured CO_2 from the sources to the reservoirs, again Freund *et al.* (2002) mention a likely range of US\$1-3/tCO_2/100 km (US\$3.7-11/tC/100 km). Using the mean value and a pipeline length of 250 km, we arrive at US\$5/t CO_2/250 km (or US\$18.3/tC/250 km), the figure used here. It must be noticed that in pipeline transportation significant economies-of-scale can be achieved.

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[10] Kreutz *et al.* (2003) present the costs of the hydrogen sulfide (H_2S) absorption, conversion and purification system differently to other authors (for example, Parsons and Shelton, 2002) who include the costs of H_2S removal (excluding the Claus and SCOT units) in the cost of the SELEXOL unit. Adding H_2S removal costs, minus the costs of the Claus and SCOT units, raises the cost of the SELEXOL system to a similar level as in Parsons and Shelton (2002).

Appendix C. Learning Curves for the Technology Components in ERIS

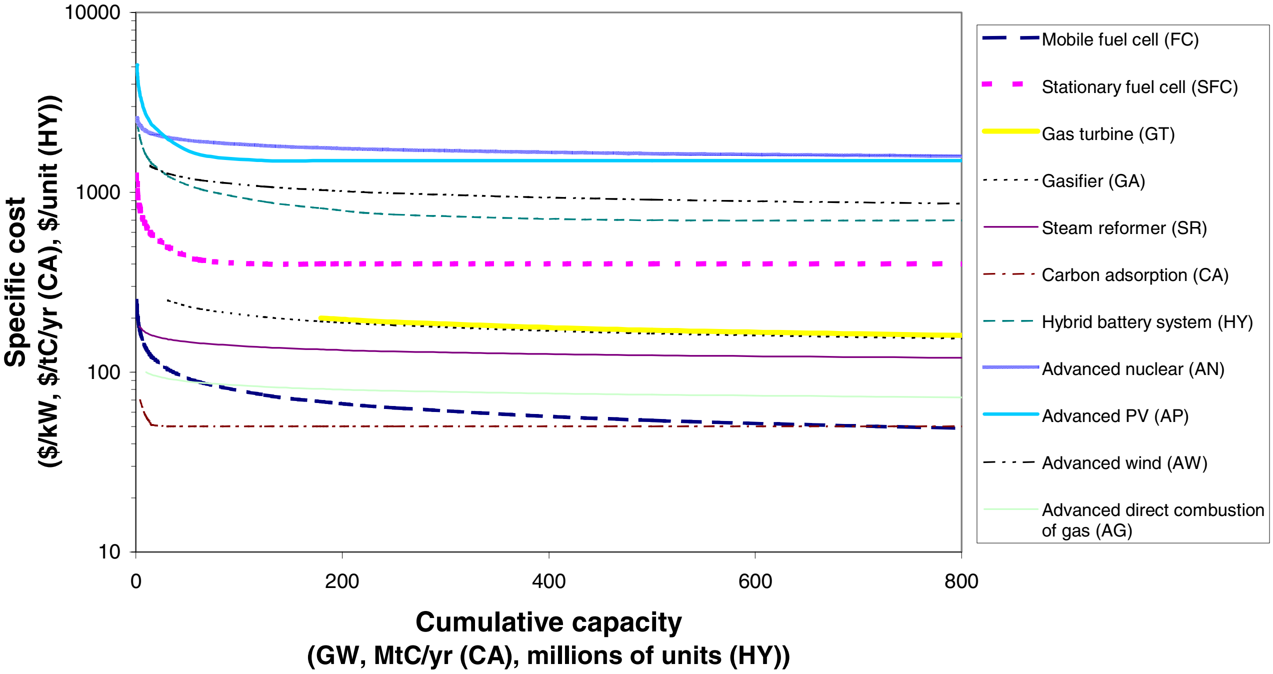

Figure C1: One-factor learning curves for the technology components in the ERIS model. Specific costs are given in US$ dollars per kW, with the exception of the carbon adsorption system (US$/t /yr) and the hybrid battery system (US$/unit).

Acronyms and Abbreviations

1FLC	one-factor learning curve
2FLC	two-factor learning curve
AFR	Sub-Saharan Africa
C	carbon
CH_4	Methane
CO_2	carbon dioxide
CPA	Centrally Planned Asia
D&D	demonstration and deployment
DG	Directorate-General
EC	European Commission
ECS	Environmentally Compatible Energy Strategies (IIASA)
EDGAR	Emission Database for Global Atmospheric Research
EEU	Eastern Europe
ERIS	Energy Research and Investment Strategies (model)
FC	fuel cell
FSU	Newly independent states of the Former Soviet Union
GHG	greenhouse gas
H_2S	hydrogen sulfide
ICE	internal combustion engine
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LAM	Latin America and the Caribbean
LP	linear program(ming)
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MEA	Middle East and North Africa
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MIP	mixed integer program(ming)
N_2O	nitrous oxide
NAM	North America
NLP	non-linear program(ming)
OECD	Organization for Economic Co-operation and Development
PAO	Pacific OECD
PAS	Other Pacific Asia
PEM	polymer electrolyte/proton exchange membrane
PSI	Paul Scherrer Institute, Switzerland
R&D	research and development
RES	reference energy system
SAPIENTIA	Systems Analysis for Progress and Innovation in Energy Technologies for Integrated Assessment
SAS	South Asia
SCOT	Shell Claus Off-gas Treatment
SELEXOL	Carbon dioxide physical adsorption process
SO_2	sulfur dioxide
SO_4^{2-}	sulfate anion
SR	steam reformer
SRES	Special Report on Emissions Scenarios (IPCC)
t	ton
TAR	Third Assessment Report (IPCC)
TEEM	Energy Technology Dynamics and Advanced Energy System Modeling
W	watt
WEU	Western Europe and Turkey

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