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Analysis of Policies Contributing to Sustainability of the Global Energy System Using the Global Multi-regional MARKAL Model (GMM)

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Peter Rafaj

MSc., Comenius University Bratislava, Slovakia

born September 25, 1972

citizen of Slovak Republic

accepted on the recommendation of

Prof. Dr. Alexander Wokaun, examiner

Prof. Dr. Konrad Hungerbühler, co-examiner

Socrates Kypreos, co-examiner

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Table of contents

Acknowledgements iii
Table of contents v
List of figures viii
List of tables x
Abstract xi
Kurzfassung xiii
1. Introduction 1
  1.1. Motivation 1
  1.2. Sustainable energy strategies and scope of analysis 2
  1.3. Structure of the thesis 5
2. Policies for sustainable global energy system 7
  2.1. Point of departure 7
    2.1.1. Human induced climate change 7
    2.1.2. Unreliable energy supplies and resource scarcity 9
    2.1.3. Air pollution 10
    2.1.4. Insufficient access to modern energy supply 11
  2.2. Exploring the chances for sustainable energy system 11
    2.2.1. Defining goal of sustainable policies 12
    2.2.2. Changing course of actions 12
    2.2.3. Climate response policies 13
    2.2.4. Promotion of renewables 14
    2.2.5. Reduction of air pollution 15
    2.2.6. Promoting technological progress 16
    2.2.7. Combining policy instruments 18
  2.3. Sustainable energy scenarios 18
3. Modelling framework 22
  3.1. MARKAL model and GMM features 22
  3.2. Characteristics of the energy supply technologies 26
  3.3. Endogenous technological learning 28
  3.4. Partial equilibrium and elastic end-use demands 29
  3.5. Trade between regions 33
4. Defining Baseline scenario and basic assumptions 34
5. International flexible policies for CO_2-mitigation 41
  5.1. Scenarios 43
    5.1.1. CO_2 emissions targets 44
    5.1.2. Hot air 47
    5.1.3. Specification of emissions trade 48
  5.2. Scenario Results 48
    5.2.1. Structural changes 48
      5.2.1.1. Electricity generation 48
      5.2.1.2. Primary energy consumption 51
      5.2.1.3. Final energy demand 52
    5.2.2. Environmental impacts 53
      5.2.2.1. Global CO_2 emissions 53
      5.2.2.2. Break-down of CO_2 reduction components 55
      5.2.2.3. Inter-regional trading of CO_2 emission permits 56
    5.2.3. Global indicators 57
    5.2.4. Cost impacts 60

5.2.4.1. Carbon permit price ... 60
5.2.4.2. Total system cost ... 61
5.3. Summary and concluding remarks ... 62
6. The role of non-CO_2 greenhouse gases in flexible climate-response policies ... 66
6.1. Description of the MAC approach ... 69
6.1.1. Definition of baseline emissions ... 69
6.1.2. Definition of marginal abatement cost curves ... 69
6.1.3. Computation of abatement and remaining emissions ... 72
6.1.4. Limitations ... 74
6.2. Scenarios ... 75
6.3. Scenario Results ... 77
6.3.1. Structural changes ... 78
6.3.2. Environmental impacts ... 80
6.3.2.1. Global CO_2 emissions ... 80
6.3.2.2. Break-down of GHG reduction components ... 82
6.3.3. Cost impacts ... 83
6.3.3.1. Carbon-equivalent permit price ... 83
6.3.3.2. Total system cost ... 83
6.3.4. Parametric analysis ... 85
6.4. Summary and concluding remarks ... 87
7. Renewable portfolio and subsidy schemes to promote renewable electricity sources ... 90
7.1. Scenarios ... 92
7.1.1. Renewable technologies in GMM and their potentials for power generation ... 92
7.1.2. Renewable portfolio standard ... 93
7.1.3. Subsidy scheme ... 96
7.1.4. Trading of green certificates ... 98
7.2. Scenario Results ... 99
7.2.1. Structural changes ... 99
7.2.1.1. Electricity generation ... 99
7.2.1.2. Role of renewable technologies under policy scenarios ... 102
7.2.1.3. Inter-regional trading of green certificates ... 106
7.2.1.4. Primary energy consumption ... 108
7.2.1.5. Final energy demand ... 109
7.2.2. Environmental impacts ... 110
7.2.3. Cost impacts ... 111
7.2.3.1. Green certificates price ... 111
7.2.3.2. Electricity generation cost analysis (example of SPV) ... 114
7.2.3.3. Total system cost ... 115
7.3. Summary and concluding remarks ... 117
8. Internalisation of external cost ... 120
8.1. Scenarios ... 122
8.1.1. External cost specification ... 123
8.1.2. Alternative approaches in externality valuation and scaling ... 125
8.1.3. Treatment of external costs in MARKAL model ... 127
8.2. Scenario Results ... 128
8.2.1. Structural changes ... 128
8.2.1.1. Electricity generation ... 128
8.2.1.2. Primary energy consumption ... 132
8.2.1.3. Final energy demand ... 133
8.2.2. Environmental impacts ... 134

8.2.2.1. Global CO_2 emissions 135
8.2.2.2. Break-down of CO_2 reduction components 136
8.2.2.3. Emissions of air pollutants 137
8.2.3. Global indicators 138
8.2.4. Cost impacts 139
8.2.4.1. Electricity generation cost analysis 139
8.2.4.2. Total system cost 142
8.3. Summary and concluding remarks 145
9. Combined policy instruments and synthesis of results 148
9.1. Scenarios 149
9.2. Scenario Results 150
9.2.1. Structural changes 151
9.2.1.1. Electricity generation 151
9.2.1.2. The role of nuclear energy in the sustainable energy policies 154
9.2.1.3. Primary energy consumption 158
9.2.2. Environmental impacts 159
9.2.2.1. Global CO_2 emissions 159
9.2.2.2. Emissions of air pollutants 161
9.2.3. Global indicators 162
9.2.4. Cost impacts 163
9.2.4.1. Carbon permit price 163
9.2.4.2. Green certificates price 164
9.2.4.3. Total system cost 165
9.2.4.4. Average policy cost 168
9.3. Robustness of scenario results 170
9.3.1. Sensitivity to the choice of discount rates 170
9.3.2. Sensitivity to the learning rate 173
9.4. Summary and concluding remarks 175
10. Conclusions and policy recommendations 178
10.1. Implications of policy instruments for a sustainable energy system 179
10.2. Structural energy-system changes 182
10.3. Environmental and cost impacts 184
10.4. Secondary benefits versus trade-offs and synergies 187
10.5. Final message 188
10.6. Outlook for further research 188
Nomenclature/abbreviations 191
References 195
Curriculum vitae 204

List of figures

Figure 1: *Global CO_2 emissions from fossil fuels and industry in the B2 scenario family.* 8
Figure 2. *Scheme of basic steps in policy-making for a sustainable energy system.* 13
Figure 3.*"Top-level" energy flows within MARKAL.* 23
Figure 4. *Definition of the five world regions in the GMM model.* 24
Figure 5. *Reference energy system (RES) applied in GMM.* 25
Figure 6. *Illustration of partial equilibrium between demand and supply.* 32
Figure 7. *Time dependence of population and gross domestic product per region in the illustrative B2 scenario.* 35
Figure 8. *Energy-related CO_2 and SO_2 emissions in the Baseline scenario.* 36
Figure 9. *Global primary energy demand by fuel and by region in the Baseline scenario.* 36
Figure 10. *Development in global electricity production by fuel and by region in the Baseline scenario.* 37
Figure 11. *Change in the global GDP/capita and PE/capita relative to the levels in the year 2000, and the time evolution of the primary energy intensities as a function of PE/capita by region in the Baseline scenario.* 39
Figure 12. *Change in the global CO_2/capita and CO_2/GDP relative to 2000, and the time evolution of carbon intensities as a function of CO_2/capita by region in the Baseline scenario.* 40
Figure 13. *Regional and global CO_2 emission rates under the Baseline and CO_2-cap&trade scenario.* 46
Figure 14. *Development in the electricity production by fuel type in the carbon-constrained scenarios.* 49
Figure 15. *Contribution of technologies to the electricity generation mix in the carbon-constrained scenarios.* 50
Figure 16. *Comparison of electricity generation in the CO_2-cap&trade scenario with and without ETL* 51
Figure 17. *Change in global primary-energy use for the CO_2-mitigation policy scenarios compared to the Baseline.* 52
Figure 18. *Time evolution of final energy demand in the Baseline and in carbon-constrained scenarios.* 53
Figure 19. *Development of total global CO_2 emissions under the Baseline and carbon-constrained scenarios.* 54
Figure 20. *Break-down of CO_2 reduction components under carbon-constrained scenarios.* 56
Figure 21. *Time dependence of inter-regional trading with CO_2 emissions permits.* 57
Figure 22. *Development in selected global indicators under Baseline and carbon-constrained scenarios.* 58
Figure 23. *Development of regional CO_2 emissions per Capita under the CO_2-cap&trade scenario.* 59
Figure 24. *Projection of changes in energy and carbon intensity over the Baseline for carbon-constrained scenarios.* 59
Figure 25. *Marginal cost of carbon emission permits reported for selected CO_2-mitgation scenarios versus time.* 61
Figure 26. *Relative change in the cumulative energy system cost over the Baseline for the CO_2-cap&trade scenario.* 62
Figure 27. *Shares of global greenhouse gas emissions in 1995 by emission species and by sources of origin.* 67
Figure 28. *Illustration of the effect of multigas abatement strategy using the MACs approach.* 70
Figure 29. *Illustration of the effect of technical multipliers to shift MAC curves out into future periods.* 72
Figure 30. *Global GHG emissions and the reduction targets in the CO_2- and Multigas-mitigation scenarios.* 77
Figure 31. *Change in global electricity generation over the Baseline scenario for C-eq abatement scenarios.* 79
Figure 32. *Contribution of technologies to the electricity generation mix in 2050 in C-eq constrained scenarios.* 80
Figure 33. *Multigas emissions reduction under an illustrative Multigas-cap&trade scenario.* 81
Figure 34. *Change in the global CO_2, CH_4 and N_2O emissions relative to the Baseline in the Multigas-cap&trade scenario and Multigas (CO_2-only)-cap&trade mitigation scenarios.* 81
Figure 35. *Break-down of GHG reduction components for the Multigas-cap&trade and Multigas (CO_2-only)-cap&trade scenarios.* 82
Figure 36. *Marginal cost of C-eq emission permits for scenarios adopting different type of flexibility in the GHG mitigation.* 84
Figure 37. *Change in the cumulative discounted energy system cost and the welfare loss due to demand reductions relative to the Baseline for scenarios adopting different type of flexibility in the GHG mitigation.* 85
Figure 38. *Comparison of increases in total system costs over the Baseline for selected variants of the Multigas-cap&trade scenario differing on assumptions about the seed value for initial abatement, maximum growth rate of abatement and the technical multipliers.* 86
Figure 39. *Influence of the maximum growth constraint of abatement on resulting global methane emissions from coal and natural gas production sectors.* 87
Figure 40. *Development in power generation by fuel under the Baseline and Renewable portfolio scenarios.* 100
Figure 41. *Power generation from non-hydro renewable sources and hydropower in the Baseline and under the subsidy scheme scenarios.* 101
Figure 42. *Change in power generation by fuel relative to the Baseline under different level of subsidy.* 102
Figure 43. *Contribution of technologies to the global electricity generation mix in 2050 in renewable-policy scenarios.* 103

Figure 44. *Penetration of renewable-electricity generation technologies in 2030 and 2050 under selected modalities of the Renewable portfolio scenario.* 104
Figure 45. *Power generation from non-hydro renewable electricity technologies under different level of subsidies.* 105
Figure 46. *Regional distribution of the additional renewable electricity generation under 2 ¢/kWh subsidy level.* 106
Figure 47. *Trade of green certificates for the Renewable portfolio and the Subsidy-2¢ scenarios.* 107
Figure 48. *Change in global primary-energy use for the Renewable portfolio scenario by fuel over the Baseline.* 108
Figure 49. *Change in the primary energy consumption over the Baseline for different subsidy levels.* 109
Figure 50. *Change in electricity consumption over the Baseline for Renewable portfolio and different subsidy level.* 110
Figure 51. *Change in CO_2 emissions in the renewable policy scenarios relative to the Baseline.* 111
Figure 52. *Marginal cost of green certificates and the relative share of renewables in the total power generation under the Renewable portfolio policies.* 112
Figure 53. *Marginal cost of green certificates and the relative share of renewables in the total power generation under different level of subsidy.* 113
Figure 54. *Generating cost for SPV and the subsidy level for 2¢ and 6¢ cases.* 114
Figure 55. *Change in the total discounted system cost relative to the Baseline for different modalities of the Renewable portfolio scenario.* 116
Figure 56. *Change in the total discounted system cost under different level of subsidy relative to the Baseline.* 117
Figure 57. *Development in global electricity production by fuel under the Baseline and externality scenarios.* 129
Figure 58. *Change in global power generation by fuel with respect to the Baseline under scenarios assuming different scaling of local external cost.* 130
Figure 59. *Contribution of technologies to the global electricity generation mix in 2050 in the Baseline and externality scenarios.* 131
Figure 60. *Change in global primary energy consumption over the Baseline for the externality scenarios.* 132
Figure 61. *Time evolution of fuel shares in total final energy demand in the Baseline and in externality scenarios.* 133
Figure 62. *Change in global electricity consumption relative to the Baseline for the externality scenarios.* 134
Figure 63. *Change in the global air emissions in the externality scenarios relative to the Baseline.* 135
Figure 64. *Development of global CO_2 emissions under the Baseline and externality scenarios.* 136
Figure 65. *Break-down of CO_2 reduction components under externality scenarios.* 137
Figure 66. *Development of SO_2 and NO_x emissions under the Baseline and externality scenarios.* 138
Figure 67. *Development in selected global indicators under the Baseline and externality scenarios.* 139
Figure 68. *Break-down of the cost components for power generation by scenarios in 2050 (example region ASIA).* 141
Figure 69. *Development of the total undiscounted system cost under externality scenarios.* 143
Figure 70. *Change in the cumulative energy system cost for the externality scenarios relative to the Baseline.* 144
Figure 71. *Development in global electricity production by fuel under the Baseline and policy scenarios.* 152
Figure 72. *Change in the global renewable power generation for policy scenarios over the Baseline.* 153
Figure 73. *Contribution of technologies to the global electricity generation mix in 2050 in the Baseline and policy scenarios.* 154
Figure 74. *Change in the global nuclear power generation with respect to the Baseline under policy scenarios.* 156
Figure 75. *Regional distribution of the additional nuclear electricity generation capacities relative to the Baseline.* 158
Figure 76. *Time evolution of global primary energy consumption by fuel under the Baseline and policy scenarios.* 159
Figure 77. *Change in global carbon emissions relative to the Baseline for single and combined policy scenarios.* 160
Figure 78. *Change in the global SO_2 and NO_x emissions in the policy scenarios relative to the Baseline.* 161
Figure 79. *Projection of changes in energy and carbon intensity relative to the Baseline for policy scenarios.* 162
Figure 80. *Marginal cost of CO_2-emission permits for scenarios combining CO_2 reduction with other sustainability objectives.* 163
Figure 81. *Marginal cost of green electricity certificates for selected scenarios combining the Renewable portfolio standard with other sustainability objectives.* 165
Figure 82. *Change in the cumulative discounted energy system cost relative to the Baseline scenario for single-and combined policy scenarios.* 166
Figure 83. *Comparison of cost and secondary benefits for selected single- and combined-policy scenarios.* 168
Figure 84. *Change in the cumulative discounted energy system cost relative to the Baseline scenario in relation to different discount rates.* 171
Figure 85. *Influence of the discount rate on the market penetration of selected technologies under the Baseline and CO_2-cap&trade scenario.* 173
Figure 86. *Influence of the learning rate on the market penetration of selected technologies under the Baseline and CO_2-cap&trade scenario.* 174

List of tables

Table 1. *Availability of global energy resources.* 9
Table 2. *Policies for addressing human-induced climate change.* 14
Table 3. *Policies for introduction and use of renewable energy sources.* 15
Table 4. *Policies for limiting impacts of energy-related air pollution.* 16
Table 5. *Policies for stimulation of technological progress and innovation.* 17
Table 6. *Matrix of policy scenarios.* 21
Table 7. *Generic end-use technologies applied in GMM and sector-specific price elasticities.* 26
Table 8. *Cost and performance of power generation technologies in the GMM model.* 27
Table 9. *Assumptions for renewable and nuclear electricity sources applied in GMM.* 28
Table 10. *Electricity generation technologies for which technology learning is endogenized in GMM.* 29
Table 11. *Carbon-emission reduction targets in the* CO_2*-cap&trade scenario.* 43
Table 12. *Naming and description of the* CO_2*-abatement policy scenarios.* 44
Table 13. *Naming and description of the multi-gas abatement policy scenarios.* 76
Table 14. *Potentials for renewable electricity generation in GMM.* 94
Table 15. *Relative share of renewable electricity production forced by the Renewable portfolio standard scenario.* 95
Table 16. *Naming and description of the Renewable portfolio standard policy scenarios.* 96
Table 17. *Subsidy levels for renewable electricity generation applied in GMM.* 96
Table 18. *Naming and description of the renewable subsidy scheme scenarios.* 98
Table 19. *Naming and description of the externality scenarios.* 123
Table 20. *Reference data for regional adjustment of the external cost.* 123
Table 21. *Basic assumptions made for the regional external cost calculation.* 124
Table 22. *External costs applied for five world regions in GMM in ¢/kWh.* 125
Table 23. *Regional adjustment of external cost to GDP.* 126
Table 24. *Increase in average shadow price of electricity in externality scenarios relative to the Baseline.* 142
Table 25. *Cumulative global damages associated to air pollution and* CO_2 *emissions.* 145
Table 26. *Naming and description of the combined-policy scenarios.* 150
Table 27. *Estimates of cumulative production of nuclear spent fuel and other radioactive materials.* 156
Table 28. *Average undiscounted cost of policy instruments for selected group of indicators.* 169

Abstract

A sustainable energy system can be characterized as a system wherein the production and use of energy resources support long-term social and economic human development while staying compatible with environmental balance. Strong indications exist today that continuation along the current energy-system development path, and the anticipated rate of change over the foreseeable future, are not compatible with key elements of sustainability.

This thesis assesses the impact of an illustrative portfolio of policy instruments that address different sustainability concerns for the global energy system in the areas of climate change, air pollution and introduction of renewable energy resources. The effects of a policy set implemented either individually or in combination were examined using the multi-regional, energy-system Global MARKAL Model (GMM), which is a "bottom-up" (technology-based) partial-equilibrium model that provides a detailed representation of energy technologies and endogenizes technology learning.

The policy instruments investigated include: a) cap-and-trade strategy imposing a CO_2 emission-reduction target on the global energy system; b) a subsidy scheme for promotion of renewable energy sources and a renewable portfolio standard that forces a minimum share of renewable electricity generation coupled with trading of green certificates; and c) the internalisation of external costs of power generation associated with air pollution and global warming. In addition, a set of combined-policy-scenarios was developed to analyse cross-policy interaction and potential synergies.

Implementation of flexible mechanisms in climate-response policies, that aims at stabilisation of energy-related CO_2 emission rates to a global level of 10 GtC/yr by the year 2050, results in significant reductions in the energy system cost and marginal costs of carbon abatement, as well as in an increasing diffusion of low-carbon technologies as compared to a mitigation regime without flexibility. The flexibility mechanisms refer to “where” and “when” flexibility in CO_2-mitigation, thereby allowing for a cost-efficient distribution of the global carbon budget over the world regions and over time.

Consideration of non-CO_2 greenhouse gases enhances the flexibility in emissions abatement by identifying an optimal trade-off between offending gases. Multigas strategies involve “what” flexibility in the mitigation process and moderate further the overall policy-induced economic penalties.

A renewable-energy portfolio standard was chosen as a regulatory instrument that favours renewable power production. The resulting prices of green certificates traded globally across regions confirm the feasibility of significant increase in penetration of renewables over the present levels at an affordable cost. The forced 35% market share of renewables in the electricity mix, however, is also associated with considerable reductions in electricity demand. Application of a subsidy scheme that provides an incentive to renewable-power suppliers accelerates initially the market penetration of renewables but does not reinforce the continuous market gains beyond the periods of direct monetary support.

External costs adopted in the electricity sector are based on assumptions related to environmental and health damages under the European conditions, and were adjusted to other world regions. Internalisation of externalities into the price of electricity changes the competitiveness of supply options in favour of non-fossil generation systems, as well as favouring power plants with emission control. Structural changes and fuel switching in the electricity sector result in significant reductions of emissions of air-polluting substances as well as CO_2.

Application of single or combined policy instruments changes substantially the structure and environmental performance of the electricity generation sector. The portfolio of technology options that emerges from the scenario analysis includes natural gas combined cycle, nuclear power plants, advanced coal systems with moderate SO_2/NO_x emissions rates and with CO_2-capture. Within the set of renewable-energy systems, the most promising are wind turbines, hydropower and biomass plants.

The decarbonisation effect of exogenously imposed sustainable policies is accompanied by a significant reduction of local and transboundary air pollution. These secondary benefits attendant to this multiple emission abatement might offset the direct cost of policy implementation. These positive environmental and economic effects are amplified when a range of policy instruments are adopted simultaneously, which illustrates quantitatively the potential for synergies between three energy-policy domains investigated.

Kurzfassung

Ein nachhaltiges Energiesystem lässt sich dadurch charakterisieren, dass Produktion und Verbrauch von Energieressourcen die zukünftige soziale und wirtschaftliche Entwicklung der Menschheit in umweltgerechter Weise fördern. Die Anzeichen deuten auf Basis heutigen Wissens deutlich darauf hin, dass eine Fortsetzung der gegenwärtigen Entwicklung des Energiesystems und die derzeit erwarteten Veränderungen mit den Zielen einer nachhaltigen Entwicklung nicht im Einklang stehen.

Die vorliegende Arbeit schätzt in diesem Zusammenhang die Auswirkungen beispielhafter politischer Strategien auf verschiedene Aspekte der Nachhaltigkeit eines globalen Energiesystems ein, speziell in den Bereichen Klimawandel, Luftverschmutzung und Einführung erneuerbarer Energien. Zu diesem Zweck wurden die Auswirkungen einzelner Massnahmen oder von Massnahmenbündeln mit Hilfe des multi-regionalen Energiemodells ‚Global MARKAL Model' (GMM), ein „bottom-up" partielles Gleichgewichtsmodell, das Energietechnologien detailliert abbildet und technologisches Lernen endogenisiert, untersucht.

Nachfolgende politische Strategien werden in dieser Arbeit behandelt: a) eine Beschränkung der CO_2-Emissionsrechte des globalen Energiesystems mit internationalem Zertifikatehandel; b) Subventionen zur Förderung erneuerbarer Energien und das Festlegen von Mindestanteilen erneuerbarer Energien bei der Elektrizitätsproduktion zusammen mit dem Handel von grünen Energiezertifikaten; und c) die Internalisierung externer Kosten der Stromerzeugung im Zusammenhang mit Luftverschmutzung und globaler Erderwärmung. Zusätzlich wurden verschiedene Szenarien entwickelt, mit Hilfe derer das Zusammenwirken verschiedener Politikstrategien auf mögliche Interaktionen und potentielle Synergien untersucht wurde.

Die Einführung flexibler Klimaschutzstrategien, die die Stabilisierung energetisch bedingter CO_2-Emissionen auf einem Level von 10 GtC pro Jahr bis 2050 vorsehen, führt zu signifikanten Reduktionen der Energiesystemkosten und der marginalen Kosten der Verringerung von Kohlenstoffemissionen. Im Vergleich zu Instrumenten, die keine Flexibilität zulassen, fördern flexible Instrumente gleichzeitig den Einsatz von kohlenstoffarmen Technologien. Die Kosten einer solchen Klimaschutzstrategie lassen sich beträchtlich mindern, wenn bei der Implementierung der Politikinstrumente die Flexibilität hinsichtlich des Zeitpunkts und des Ortes der Emissionreduktion optimal genutzt werden.

Wenn die CO_2 bezogene Klimaschutzstrategie durch die kompensierende Minderung anderer Treibhausgase als weiteres flexibles Politikinstrument zugelassen wird, können die gesamten Vermeidungskosten zusätzlich gesenkt werden.

Das Festlegen von Mindestanteilen erneuerbarer Energien wurde als Regelinstrument zur Förderung der Elektrizitätsproduktion aus erneuerbaren Energien gewählt. Die daraus resultierenden Preise global gehandelter grüner Energiezertifikate zeigen, dass ein signifikanter Anstieg des Marktanteils erneuerbarer Energien über heutige Anteile zu moderaten Kosten erreichbar ist. Dennoch führt das Ziel eines Anteils erneuerbarer Energien von 35% an der Stromerzeugung zu deutlichen Rückgängen in der Elektrizitätsnachfrage. Die alternative Einführung von Subventionen stellt eine Art finanzielle Starthilfe dar, die zwar anfänglich zu einem vermehrten Einsatz der Erneuerbaren führt, aber nicht ausreicht, um sie auf Dauer gegen die konventionellen Energietechnologien durchzusetzen.

Die hier verwendeten externen Kosten der Stromerzeugung beziehen sich auf Annahmen für lokale Umwelt- und Gesundheitsschäden unter Europäischen Bedingungen, und wurden für andere Regionen der Welt angepasst. Die Internalisierung von Externalitäten im Elektrizitätspreis verschiebt die Wettbewerbsfähigkeit bei der Stromerzeugung zugunsten nicht-fossiler Systeme und Anlagen mit Emissionskontrolle. Strukturelle Veränderungen und der Wechsel des Brennstoffs im Elektrizitätssektor führen zu einer erheblichen Reduktion der Emissionen luftverunreinigender Substanzen und CO_2.

Die Frage der Anwendung einzelner Massnahmen oder ganzer Massnahmenbündel hat deutliche Auswirkungen auf die Struktur der Elektrizitätsproduktion und seiner Umweltauswirkungen. Die vorliegende Szenarienanalyse legt nahe, dass aus Sicht der Nachhaltigkeit Technologien wie GuD-Kraftwerke, Kernkraftwerke sowie fortschrittliche Kohlekraftwerke mit geringen SO_2/NO_x Emissionen und CO_2-Rueckhaltung erfolgversprechend sind. Bei den erneuerbaren Energietechnologien erscheinen Windkraft-, Wasserkraft- und Biomasseanlagen als aussichtsreich.

Die Senkung von CO_2-Emissionen durch eine nachhaltige Umgestaltung des Energiesystems geht einher mit einer signifikanten Reduktion lokaler und grenzüberschreitender Luftverschmutzung. Solche Nebeneffekte einer nachhaltigen Politikstrategie können die direkten Kosten der Massnahme aufwiegen. Die positiven Umwelt- und Kosteneffekte ergänzen und vergrössern sich, wenn verschiedene Massnahmen simultan eingesetzt werden, was das Potential für Synergien zwischen drei energiepolitischen Strategien deutlich macht.

1. Introduction

1.1. Motivation

Energy production, conversion and use are linked directly to sustainable development. This relationship is based on two premises that are of fundamental importance for the whole concept of sustainability. First, the access to adequate energy services for meeting the human needs and availability of reliable energy resources are necessary for achieving economic prosperity and enhanced social welfare. Secondly, energy systems always produce environmental burdens that can jeopardize the quality of life of present and future generations, and at the same time may violate the carrying capacity of local, regional or global ecologic and climatic systems.

A number of recent comprehensive analysis show that continuing along the current path of energy system development, and the anticipated rate of change attendant to that path, are not compatible with key elements of sustainability (UNDP, 2000; IEA, 2001a; Schrattenholzer et al., 2004). To reverse this trend and to alter the performance of energy systems towards sustainable energy futures will require changes in a range of factors comprising consumer attitude and behaviour, political priorities, technology adoption, etc. More specifically, sustainable development of the energy sector is not conceivable without increases in energy efficiency, utilization of new advanced supply technologies, and a higher rate of exploitation of renewable resources.

A prerequisite for approaching pathways that resonate with sustainability objectives in energy supply and use are appropriate strategies and policy frameworks that stimulate the changes in directions of technological progress, investments and deployment of new technologies. The key issues that policy instruments must take into consideration are the improved access to modern and affordable energy technologies and elimination of environmental, safety and health effects associated with energy use.

In this context, it is relevant to examine the effects of policy measures that could contribute to the quest towards a sustainable global energy system and the role of advanced energy technologies in achieving this long-term goal. Impact assessment of policy instruments has become an important element of the policy development process. Impact assessment represents a systematic attempt to shed light into the possible effects of policy proposals; as such, it serves as an aid to the decision-making process. For example, impact assessment plays an important role in the implementation of the sustainable-development strategies of the European Commission (EC, 2002), among others.

The development of quantitative energy scenarios (Nakićenović et al., 1998) provides a useful tool for analysing impacts of strategies and policies applied on energy systems. Energy scenarios are typically designed by using formal energy system models to enhance understanding of future developments in energy systems. Scenarios provide insights into the behaviour of energy systems under selected policy regimes, quantify the impacts of strategies applied on a local, regional or global level, and provide a framework for exploring a wide range of technology configurations and options.

The objective of this thesis is to assess impacts and implications of different sustainable energy policies on the basis of energy scenarios developed for the "bottom-up" energy-planning model MARKAL and to analyse the role of advanced technology options in contributing to the fulfilment of selected long-term sustainability goals.

1.2. Sustainable energy strategies and scope of analysis

Driving the global energy system along a sustainable path is progressively becoming a major concern and policy objective (EC, 2005; Kok and de Coninck, 2005). The emergence of a sustainable global energy system, however, is a gradual long-term process that will require a profound transformation of the current energy-systems structure. Addressing this multi-dimensional challenge requires a long-term systematic perspective and the integration of many different social, economic, environmental and technological elements and constraints.

In general, four key policy strategies can be identified that support sustainable development of the global energy system:

I. **Restructuring energy sector by use of regulatory measures:** governments apply goals and targets for performance characteristics of energy system. Examples of regulatory measures are air-pollution and greenhouse gas emission limits, efficiency standards, or targets mandating that a specific fraction of energy originates from renewable sources.

II. **Elimination of energy market distortions:** the set of policies attempting to overcome imperfections in energy markets, which in many instances do not account for social, health and environmental costs of energy supply and use. Market distortions can be limited by internalisation of external cost of energy in a form of energy taxes, or through targeted, time-limited subsidies for emerging technologies.

III. **Setting frameworks for international cooperation:** the way to move national efforts in reaching sustainability goals on regional and international levels. The options for this policy strategy include international emission trading, harmonisation of taxes and environmental standards, as well as international transfer of know-how.

IV. **Investments in advanced technologies and support of technological innovation:** the creation of a political and legislative framework encouraging the private sector to invest in modern energy systems on a large scale. Additionally, policies in favour of research, development, and deployment must help to remove barriers that restrain the penetration of promising technologies in the market.

Performance of the above-listed sustainable policy strategies can be measured by defining a set of indicators that characterise the achievements of the respective strategy and indicates how selected strategies comply with the overall sustainability in comparison with each other. Examples of sustainability indicators are:

- Increasing human welfare
- Increasing access to energy services
- Increasing affordability of energy
- Reducing local and transboundary air pollution
- Mitigation of greenhouse gas emissions
- Limiting negative health impacts
- Reducing waste production
- Improving security of energy supply
- Reducing fossil fuel dependency
- Improving energy conversion efficiency
- Acceleration of technology innovation and diffusion

Ranking and weight associated with each of the sustainability indicator depends on priorities given to specific objectives of applied strategy and may be arbitrary. It is important to recognize that a number of overlaps exist among sustainable policy strategies and the goals they try to address. For example, a targeted policy instrument that aims at the reduction of local air pollution may improve the performance of energy system in terms of higher energy efficiency or accelerated penetration of renewables.

Energy policy strategies, as outlined above, can be implemented by a broad range of specific policy instruments. While it was beyond the scope of this work to analyse all of them, the portfolio of policy instruments under investigation herein addresses four key goals that are of main importance for sustainable energy systems: a) mitigation of greenhouse gas emissions, b) promotion of renewable energy sources, c) reduction of air pollution, and d) deployment of advanced energy-supply systems.

Policy instruments considered are as follows:

- International greenhouse gas emissions reduction targets applied in combination with international emissions trading;
- Renewable portfolio standard in electricity supply and renewable electricity subsidy scheme that is complemented by international trading of green certificates;
- Internalization of external costs related to air pollutants and greenhouse gases in the electricity sector;
- Lowering the cost of new technologies for more rapid deployment.

Additionally, the impacts of applying selected combinations of policy instruments within this policy portfolio are examined.

The impacts of specific policy instruments adopted within the global energy system are examined through a set of energy-policy scenarios. Scenarios reflect various modalities of policy implementation, which refer to different levels of flexibility, trading regimes or a rate of technical progress. Quantitative results derived from scenario analysis provide a basis for inter-policy comparison. Parameters that were used as indicators of sustainability performance of respective policy instruments are: a) fossil-fuel dependency in terms of primary and final energy demand; b) penetration of advanced electricity-production systems; c) reductions in energy demand by end-users; d) changes in greenhouse gas emissions; e) reduction of air pollution, and f) total energy-system cost.

Although the analysis was conducted in the context of the regional and global energy systems as a whole, emphasis in this work is put on the global electricity sector given that, among others, the reduced number of actors and the relatively wide range of technology options as compared to other sectors make the electricity sector most likely to be one of the main targets of sustainable energy policies. The analysis has been conducted using the *G*lobal, *M*ulti-regional "bottom-up" energy-system *M*ARKAL (GMM) model (Barreto, 2001; Barreto and Kypreos, 2004; Rafaj et al., 2005a). The GMM model allows a detailed representation of energy technologies and simulates technology dynamics in energy systems under the assumption of a partial (economic) equilibrium. To achieve a consistency in the assessment of selected policy instruments, the same version of GMM has been used for all scenario analyses and the impacts of all policies are evaluated against the same baseline case.

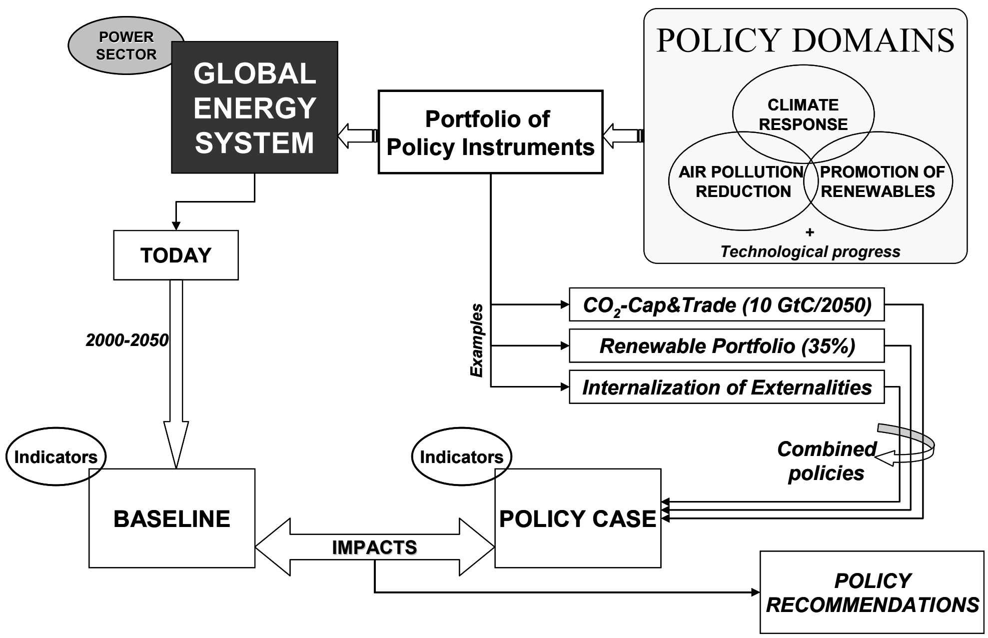
1.3. Structure of the thesis

The portfolio of policy instruments analysed in this work is put in a broader perspective of sustainability issues related to energy production and use in Chapter 2. This chapter provides an overview of policy options that are applicable to a group of four sustainability challenges: greenhouse gas (GHG) emissions mitigation; promotion of renewable-energy sources; reduction of air pollution; and accelerated deployment of advanced electricity-generation technologies. Chapter 3 describes the modelling framework used for impact assessment of sustainable energy policies. Basic elements of the MARKAL model are outlined and specific features and assumptions for the GMM version of MARKAL model are also presented in Chapter 3. Chapter 4 presents the baseline scenario used for the policy assessment. Basic drivers for the development in the reference scenario together with assumptions on efficiency improvements, technology dynamics, and fuel availability are reported.

Sustainable energy policies and selected instruments are first analyzed separately studying the impacts on the parameters listed above. In Chapter 5, an analysis of policies imposing a stringent carbon dioxide (CO_2) emission reduction target is presented, and the effects of flexibility mechanisms in climate response policies are evaluated. Chapter 6 goes a step further, and documents the role of controlling non-CO_2 gases in climate protection by exploring the benefits of "what" flexibility option in GHG mitigation strategies. Additionally, Chapter 6 describes the implementation of mitigation options for non-CO_2 gases in the GMM model. Chapter 7 is devoted to implications of two international policies adopted in this study for promoting a larger penetration of renewable electricity sources. The first policy instrument refers to a renewable portfolio standard; the second instrument under examination is a subsidy scheme for renewables. The role of international trading of green certificates is also discussed. In Chapter 8, impacts of policies that internalize external cost in power generation sector are addressed. Two different types of externality charges are imposed: external cost from air pollution and cost originating from both air pollutants and climate change.

Thereafter, selected combinations of policy instruments are reported in Chapter 9. The potential for secondary benefits, trade-offs and synergies that may result from simultaneous application of policy instruments is highlighted. In addition, this chapter provides a synthesis of the results obtained from policy-scenario analysis and compares the performance of policies by using a set of indicators. Finally, Chapter 10 outlines key policy insights and conclusions, and proposes directions for further research. The basic structure and the scope of the thesis are depicted in Box 1.

BOX 1: Scope and structure of the thesis



Results of this thesis have been published (or submitted for publication) in:

Rafaj P., Kypreos S., Barreto L. (2005a). "Flexible Carbon Mitigation Policies: Analysis with a Global Multi-regional MARKAL Model". In Haurie A. and Viguier L. (Editors): Coupling Climate and Economic Dynamics, Kluwer Academic Publishers. Dordrecht, the Netherlands.

Rafaj P., Kypreos S., Barreto L. (2005b). "Combining Policy Instruments for Sustainable Energy Systems: An Analysis with the GMM Model". Paper submitted to Environmental Modelling and Assessment.

Rafaj P., Barreto L., Kypreos S. (2005c). "The Role of Non-CO_2 Gases in Flexible Climate Policy: An Analysis with the Energy-Systems GMM Model". Paper submitted to Global Environmental Change.

Rafaj P., Kypreos S. (2005). "Internalization of external cost in the power generation sector: Analysis with Global Multi-regional MARKAL Model". Energy Policy (in press).

2. Policies for sustainable global energy system

The purpose of this chapter is to place the policy instruments under examination in this work in the broader context of sustainable development. Threats imposed on the future generations by the present development of the energy systems are outlined, and measures that may help to shift the development to a more sustainable path are discussed. Finally, the policy instruments and corresponding policy scenarios are organized in a policy-scenario matrix.

2.1. Point of departure

A sustainable energy system can be characterized as a system, in which the production and use of energy resources support the long term social and economic human development while remaining compatible within the context of a general environmental balance. The UNDP (2000) identifies the following characteristics of the current (global) energy system that do not comply with basic elements of sustainability:

- Current energy supply and use is a major source of anthropogenic GHGs that contribute to global warming and can lead to irreversible changes of the global climatic system.
- Existing energy supplies are not reliable and pose economic burdens to a large portion of humans. Dependency on fuel imports increases vulnerability of many countries as the traditional energy sources can not sustain if the overall consumption rises substantially.
- Energy-related emissions of polluting substances threaten human health and well-being, and lead to degradation of ecosystems.
- Over two billion people have no access to affordable and modern energy supplies, which seriously limits prospects for improvement of welfare and negatively influences social stability of affected regions.

These four issues are elaborated in the following subsections.

2.1.1. Human induced climate change

The extraction, transport and combustion of coal, oil and natural gas are responsible for the majority of anthropogenic greenhouse gas emissions to the atmosphere. The combustion of fossil fuels contributes about four-fifths of total GHG-emissions in the form of CO_2. The energy sector also emits a large fraction of methane (CH_4) emissions through coal, oil and gas extraction and transport, and nitrous oxide (N_2O) emissions through energy and transport

(IEA, 2001a). Current data sets presented in IPCC (2001b) show that related human activities influence atmospheric concentration of both the long-lived greenhouse gases and short-lived forcing agents. The increased concentration of greenhouse gases in the atmosphere is linked to the Earth's radiation budget and might cause changes of the global mean temperature. It is estimated that if the amount of carbon dioxide were doubled instantaneously, with everything else remaining the same, the temperature of the surface-troposphere system would increase by 1.2 to 4.5°C (IPCC, 2001b). Temperature rise will inevitably have significant impacts on water resources, food security, ecosystems, health and sea levels.

The rate of change of atmospheric concentration of CO_2 over the period 1990 to 1999 has been 1.5 ppmv/yr (IPCC, 2001b). This change might increase dramatically for the projected growth in fossil-fuel use in the energy systems of both industrialised and developing world regions. It is clear, therefore, that the energy sector needs to be at the core of action to reduce the threat of global climate change. Figure 1 provides an example of possible time evolution of energy and industry related CO_2 emissions for the B2 scenario family reported by IPCC (2000) in the Special Report on Emission Scenarios (SRES). The B2 storyline describes a world in which the emphasis is placed on the local solutions to issues of sustainable development. It refers to a "middle-of-the-road" or a "dynamics-as-usual" scenario group and is consistent with current institutional frameworks and current technology dynamics.

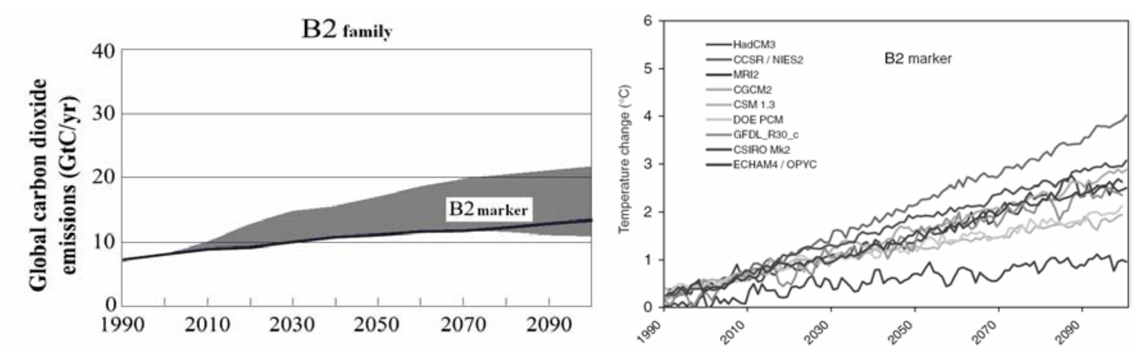


Figure 1: *Global CO_2 emissions from fossil fuels and industry in the B2 scenario family and the range of projected temperature changes for the illustrative marker B2 scenario estimated by a group of climatic models. Source: IPCC (2001b).*

Although the B2 storyline envisages a certain degree of increased concern for local environmental and social aspects, global CO_2 emissions roughly double between 1990 and 2050, and continue to rise thereafter. Atmospheric CO_2 concentration increases from present levels of 365 ppmv to around 600 ppmv by the year 2100. Anticipated mean change in global temperature until 2100, relative to 1961-1990 averages, projected by a group climatic models for the B2 marker scenario[1], is 2.2°C (with a range of 0.9 to 3.4°C) (IPCC, 2001b).

2.1.2. Unreliable energy supplies and resource scarcity

Security of the current energy supply is deficient because of a disproportionate distribution of the fossil-fuel resources across the world regions and because of limited capacity to develop other resources (UNDP, 2000). This deficiency and vulnerability of energy supply will most likely become critical in the following decades with growing global dependency on imported oil.

Approximately 80% of present-day worldwide primary-energy demand is satisfied by fossil fuels. An overall production of fossil fuels increased within the last decade by 16% for oil and 26% for natural gas (BP, 2004). Table 1 indicates the length of time that remaining proven reserves of fossil fuels would last if production were to continue at level of the year 2003 (reserves-to-production ratio). The most critical situation can be observed for the conventional oil reserves, which may last for the next ~40 years. The time availability will be shorter if the current dynamics in oil consumption in developing regions is considered.

The picture looks more optimistic when the total availability of fossil fuels includes unconventional resources and additional fuel occurrences. In this case the time availability of oil is approximately 200 years, and natural gas would last for the next 400 years. If the fuel production is dynamic and a function of projected global demand, however, the resource-to-production ratio is approximately halved.

Fuels	**Change in production (2003/1993)[a]**	**Reserves-to-production ratio (years)[a]**	**Resources-to-production ratio (years)[b]**	**Resources-to-production ratio (years)[b]**
		Static	*Static*	*Dynamic*
Oil	+16%	41	200	95
Natural gas	+26%	67	400	230
Coal	+18%	192	1500	1000
Nuclear	+21%	50	>300	

Table 1. *Availability of global energy resources. a) Source:BP (2004); b) Source: UNDP (2000).*

Clearly, from the resource point of view, the coal and uranium resources should not present a problem for the future generations. Oil and natural gas resources might last for centuries as well, however, extraction and delivery of the required unconventional resources will increase

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[1] Marker scenario represents a given scenario family and reflects the best a given storyline. B2 marker scenario has been developed by IIASA using MESSAGE model, and is described in details in Riahi and Roehrl (2000).

the marginal cost of supplied fuels to the levels that will probably exceed their large-scale affordability (not to mention added environmental impacts of exploitation of unconventional fossil-fuel resources). Furthermore, large import dependency of the current energy systems, relying on scarce fossil resources like oil, imposes a threat to the political stability and thereby detracts from the goals of sustainable development.

2.1.3. Air pollution

Current means for production and use of energy contributes considerably to environmental degradation and thereby has negative impacts to human health and ecological balance. Energy-related activities account for around 80% of anthropogenic sulphur dioxide (SO_2) emissions and more than 75% of nitrogen oxides (NO_x) emissions. Fossil-based energy systems play substantial role in releasing other emittants, particularly carbon monoxide (CO), volatile organic compounds (VOCs), CH_4, ozone (O_3), or particulate matter (PM) (UNDP, 2000). Health and environmental burdens of emissions related to the fossil fuels combustion are measurable at different levels:

- Household level: poor indoor air quality because of solid fuel burning.
- Local level: urban air pollution because of fossil-fuel use in the transportation, electricity and heat-production sectors.
- Regional level: cross-boundary acid deposition causing damage to forest and aquatic systems, crops, buildings and other structures.

Current policies applied to the problems of energy-related acidifying substances, primarily SO_2 and NO_x, result in a declining trend of emission levels in industrialised regions. Environmental regulations and adoption of the Helsinki protocol and Oslo protocol are expected to result in a 60% reduction of SO_2 emissions in Western Europe in 2020, as compared to 1990. In Central and Eastern Europe and the former Soviet Union, a 50% reduction is projected in 2020 due to structural transitions in energy sector and national policies. About 35% reduction in 2020 of SO_2 emissions as compared to 1990 levels could occur in North America following the implementation of local measures and Clean Air Act (UNDP, 2000), although presently in the US only less than 10% of the total coal based generation capacities has been retrofitted (EIA, 2001).

The problem of SO_2 and NO_x emissions, however, will remain substantial in the developing world. Modelling results (Riahi and Roehrl, 2000; UNDP, 2000) suggest that in Latin

America, Middle East and Africa the SO_2 emission levels might undergo a 30% increase by 2020, while in Asia SO_2 emission levels can even double as compared to the present. This development can have significant consequences; for example, in China about one million people die prematurely every year as the result of outdoor air pollution, and the associated damage cost corresponds to 6-7% of China's GDP in 1998 (Hirschberg et al., 2003). Emissions of NO_x are expected to follow regional patterns similar to those for SO_2; however, the situation is amplified by added emissions from the transport sector (UNDP, 2000).

2.1.4. Insufficient access to modern energy supply

Modern energy supplies, like electricity and gaseous and liquid fuels, presently are not accessible to around two-billion people world-wide. Moreover, poverty in large parts of the developing world forces millions of households to rely on traditional fuels and inefficient technologies. Besides the negative health impacts illustrated in the previous subsection, lack of electricity or other clean fuels and/or technologies limits advances in income-generating potential, households productivity, mobility, education, employment, business opportunities, and also influences indirectly demographic patterns. Limited access to commercial energy services in rural areas is one of the factors that increase migration rates and environmental pressure on rapidly growing urban centres (UNDP, 2000).

Considering the current developments, the largest growth in demand for energy services will occur in the developing countries. Application of present-day technologies will not be adequate if the projected energy demands are to be met in a sustainable way. The cross-regional deployment of advanced and highly efficient energy systems that will provide energy services at affordable cost is undoubtedly a challenging task requiring substantial investments in technology innovation.

Potential obstacles in the long term might also emerge from the expected boom in transfer of second-hand energy supply and transport technologies to emerging markets that could result in additional net environmental pollution and to widening the technological gap between developed and developing countries (Janischewski et al., 2003).

2.2. Exploring the chances for sustainable energy system

Addressing issues of sustainability for the global energy system requires a number of changes in energy supply-demand patterns, shifts in consumer behaviour and new political priorities. Promoting sustainable development in the energy sector is a long-term process that demands the establishment of policy frameworks that are vital to encourage change in the desired (sustainable) direction. This section develops a framework for quantifying means for achieving a sustainable system of energy production, conversion, and use wherein the chances for achieving such an objective can be quantitatively explored.

2.2.1. Defining goal of sustainable policies

Based on aspects of the current development of the global energy system that are not compatible with principles of sustainability, as illustrated in Section 2.1, the goals of policies under examination in this investigation are defined as follows:

I. To limit the global energy-related emissions of greenhouse gases to levels that would lead in the long run to the stabilization of the atmospheric GHG concentration at about 550 ppmv.

II. To reduce the fossil-fuel dependency of the global energy system by increasing significantly contribution of electricity produced from renewable energy sources.

III. To decrease emission levels of air-polluting substances originating from fossil-fuel combustion in the electricity generation sector.

IV. To reduce the cost of selected advanced electricity supply systems so that they penetrate in the markets at sufficient rate and help to moderate negative environmental impacts of energy production.

2.2.2. Changing course of actions

Having defined four goals (or challenges) of sustainable energy policies, it is necessary to select policy strategies that are suitable for addressing specific policy goals, and then to choose policy instruments through which these policies are implemented. The way this sustainable-policy-making process can operate is illustrated in Figure 2.

The main strategies to attain goals of sustainability in the energy sector have been identified in Section 1.2 as follows: a) restructuring energy sector by use of *regulatory measures*; b) elimination of energy market distortions using *monetary measures*; c) promoting frameworks for *international cooperation*; and d) investments in advanced technologies to stimulate *technological innovation*.

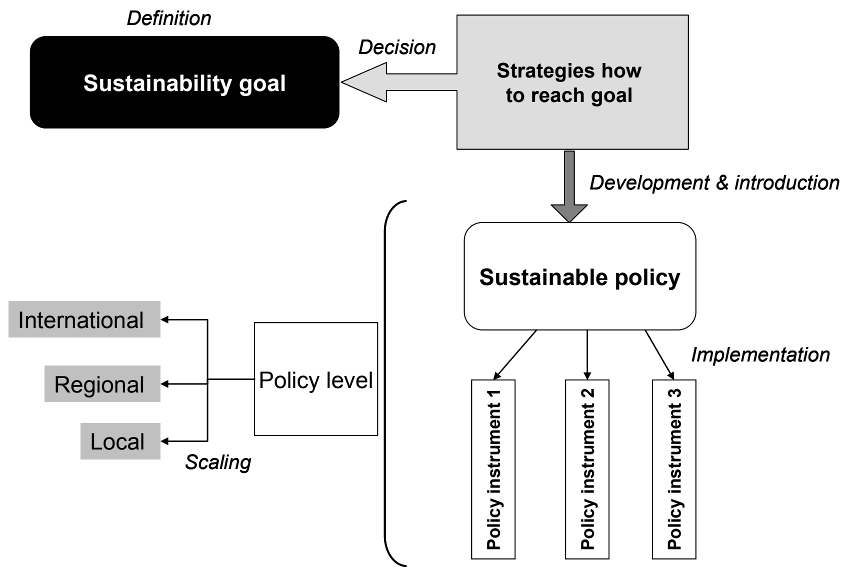

Figure 2. *Scheme of basic steps in policy-making for a sustainable energy system.*

The following section describes how different strategies evolve in a policy framework for addressing energy-related issues of climate change, renewable energy, air pollution and technical progress.

2.2.3. Climate response policies

Reduction of energy- and non-energy- related GHG emissions needed to minimise the risk of human-induced climate change is one of the most challenging sustainability tasks for both industrialized and developing countries. The United Nations Framework Convention on Climate Change (UNFCCC) adopted by its Parties in 1992 and consecutive Kyoto Protocol of 1997, established an international framework for reaching the ultimate objective of stabilising atmospheric concentrations of GHGs at a level that would prevent dangerous interference with the climate system.

The Kyoto protocol (UNFCCC, 1999) exacts from industrialized nations (grouped in Annex B of the protocol) to reduce their total GHG emissions by at least 5% over 1990 levels during the commitment period 2008-2012. The Kyoto protocol suggests international mechanisms with which the reduction entitlements can be achieved more efficiently at a minimum cost. The role of these flexibility mechanisms in a climate response policy framework is elaborated in details in Chapters 5 and 6.

The Kyoto protocol and subsequent international agreements are less specific in the choice of methods to be used for domestic reduction efforts. Adoption of proper domestic policy instruments will be essential if the GHG-reduction targets are to be met. Such policies could vary from application of "command & control" regulatory options to a carbon tax or voluntary measures. Table 2 provides an overview of different types of instruments with which the climate policies can be implemented on both domestic and international levels.

Framework:	***CLIMATE RESPONSE POLICIES***		
GOAL	**TYPE OF STRATEGY**	**POLICY INSTRUMENT (EXAMPLE)**	**LEVEL OF IMPLEMENTATION**
Limiting the energy related emissions of GHGs	Regulatory	Fuel switching	Domestic
		Efficiency standards	
		Appliance labelling	
		Reporting requirements	
	Monetary	Carbon tax	
		Phasing out subsidy for fossil energy	
		Voluntary agreements	Domestic/ International
	International cooperation	Trade of emission permits	International
		Carbon fund	
	Technology innovation	See Table 5.	Domestic/ International

Table 2. *Policies for addressing human-induced climate change.*

2.2.4. Promotion of renewables

A range of factors can be identified that are implicit to the increased supply from renewable-energy sources that can contribute to the sustainability of global energy system. Larger exploitation of the large potential of renewable energy can enhance diversity in fuel supply markets, reduce dependency on fossil supplies from politically unstable regions, moderate the environmental burden, create new employment and economic opportunities, and provide new options for meeting energy needs especially in developing countries and rural areas. Nevertheless, a number of obstacles limit the deployment of new renewable-energy technologies in today's markets, particularly high initial cost, lack of access to power networks, immaturity of technology, and insufficient awareness (IEA, 2004a; Wörlen, 2003).

Policy-making for the introduction of renewables in the energy market has been currently an area where a number of innovative policy tools and incentive schemes emerged. Examples of these policy instruments are given in Table 3. As demonstrated by Sawin (2004), applicability and success of policy instruments largely depends on local circumstances. An appropriate mix of policy tools, therefore, has to be considered so that the competitiveness of renewables will increase substantially, and the market penetration will sustain in a long term. Incentive strategies in favour of renewable energies comprise regulations, fiscal mechanisms, technology improvement and attendant cost reduction, but also information dissemination and better involvement of stakeholders.

Promoting renewable energy is on the policy agenda of many countries. For instance, the European Commission published in 1997 the *White paper and action plan for renewable energy sources* (EC, 1997) and adopted a *Directive on the promotion of the electricity produced from renewable energy source in the internal electricity market* in 2001 (Directive 2001/77/EC; EC, 2001). These documents establish an indicative EU-target and recommend that 22.1% of total electricity consumption by 2010 should originate from renewable-energy sources. It is anticipated that market mechanisms like international trading of renewable electricity certificates (or green certificates) will be a powerful flexibility tool that will help in reaching the policy target in a cost-effective way. Implications of renewable policies that foresee trading of green certificates on a global level are analysed in Chapter 7.

Framework:	***PROMOTION OF RENEWABLES***		
GOAL	**TYPE OF STRATEGY**	**POLICY INSTRUMENT (EXAMPLE)**	**LEVEL OF IMPLEMENTATION**
Reduction of fossil fuel dependency by increasing contribution of the renewable sources	Regulatory	Renewable portfolio standard	Domestic
		Obligation to buy renewable energy/Feed-in-law	
		Green tariffs	
		Building codes	
	Monetary	Tax credits	
		Direct subsidies	
		Low interest loans	Domestic/ International
	International cooperation	Trade of green certificates	International
	Technology innovation	See Table 5.	Domestic/ International

Table 3. *Policies for introduction and use of renewable energy sources.*

2.2.5. Reduction of air pollution

The 1979 Geneva Convention on Long-range Transboundary Air Pollution was the first international legally binding instrument to deal with problems of air pollution on a broad regional basis. Besides laying down the general principles of international cooperation for air pollution abatement, it set up an institutional framework bringing together research and policy. The Convention was originally initiated after scientists demonstrated the interrelationship between sulphur emissions in continental Europe and the acidification of Scandinavian lakes. The Convention was extended by several protocols dealing with the abatement of emissions of SO_2, NO_x, VOCs, Persistent Organic Pollutants (POPs) and heavy metals. The implementation of protocols led to substantial emission reductions of polluting substances in European countries (UNECE, 2004). In 1990, the United States, Canada and Mexico adopted the Clean Air Act in order to limit cross-boundary air pollution, and established a successful system for trading emission allowances (U.S. EPA, 1993).

As shown in Table 4, air pollution abatement policies can be implemented at the domestic level by using regulatory instruments or by imposing taxes that aim at internalization of external costs related to health and environmental damages. Experiences from industrialized countries show that investments in emission abatement induced by environmental policies are offset through improvements in human health and ecologic systems. It can be expected that the net benefits of reduced air pollution will be higher in the developing regions, given the level of damages and availability of abatement technologies (UNDP, 2000).

Framework:	***REDUCTION OF LOCAL AND TRANSBOUNDARY AIR POLLUTION***		
GOAL	**TYPE OF STRATEGY**	**POLICY INSTRUMENT (EXAMPLE)**	**LEVEL OF IMPLEMENTATION**
Decrease in air pollution originating from fossil fuel combustion	Regulatory	Emission limits	Domestic
		Minimum emission standards	
		Fuel quality standards	
		Emission inventories	
		Air quality standards	
		Pollution alert standards	
		Cap & trade of emission permits	Domestic/ International
	Monetary	Externality taxes	Domestic
	International cooperation	Conventions on long-range transboundary air pollution	International
	Technology innovation	See Table 5.	Domestic/ International

Table 4. *Policies for limiting impacts of energy-related air pollution.*

2.2.6. Promoting technological progress

Access to and affordability of commercial energy services is vital for the prosperity of several billion people. The ways those people improve their life and their environment is critical to the degree to which development is sustainable for the world as a whole. Promotion of advanced technology options in the energy system and associated costs, therefore, constitute a central point in the discussion of approaches to reducing adverse sustainability impacts. It is well recognized that the development and deployment of cleaner and more efficient energy technologies will have an important contributing role in facilitating the sustainability goals both in the short and long term (e.g., IEA, 2003). An important related question deals with the extent to which technologies can play this role, which policy instruments could foster their development and subsequent diffusion in the marketplace, and how much would the implementation of those policies cost.

Policy instruments, as listed in Table 5, must be designed to encourage technological progress that enables a transition to a long-term sustainable path for the global energy system. Related effects of these policies, therefore, must be examined not only in the light of short-term economic considerations (i.e., static efficiency) but also in terms of their long-run impacts (i.e., the so-called dynamic efficiency). An important facet of enhancing dynamic efficiency reflects the impact of the policy instruments on the ability of the energy system to achieve a transition in the long run towards a cleaner, more efficient, environmentally compatible and cost-effective technological path (Barreto, 2001).

<table>
<tr><th>Framework:</th><th colspan="3">PROMOTING TECHNOLOGY PROGRESS</th></tr>
<tr><th>GOAL</th><th>TYPE OF STRATEGY</th><th>POLICY INSTRUMENT (EXAMPLE)</th><th>LEVEL OF IMPLEMENTATION</th></tr>
<tr><td rowspan="16">Improved access and affordability of advanced energy systems</td><td rowspan="5">Regulatory</td><td>Green labelling schemes</td><td rowspan="9">Domestic</td></tr>
<tr><td>Identification and support of niche markets</td></tr>
<tr><td>Public procurement procedures</td></tr>
<tr><td>Capacity building</td></tr>
<tr><td>Training programmes</td></tr>
<tr><td rowspan="6">Monetary</td><td>Low-cost and guaranteed loans</td></tr>
<tr><td>Tax incentives</td></tr>
<tr><td>Buy-down programmes</td></tr>
<tr><td>Public benefits funds</td></tr>
<tr><td>Public and private investments in research and development</td><td rowspan="2">Domestic/
International</td></tr>
<tr><td>Direct financial support to demonstration projects</td></tr>
<tr><td rowspan="3">International cooperation</td><td>Direct foreign investments (incl. JI and CDM projects)</td><td rowspan="3">International</td></tr>
<tr><td>Technology and Know-how transfer</td></tr>
<tr><td>Research & development ventures</td></tr>
<tr><td>Technology innovation</td><td>Technology optimisation for developing needs</td><td>Domestic/
International</td></tr>
</table>

Table 5. *Policies for stimulation of technological progress and innovation.*

It should be recognized that implicit in all different policy frameworks discussed above is the stimulation of endogenous technological learning (ETL) via learning investments that help advanced technologies to progress along learning curves. Support of such initially more-costly technologies is important to avoid "lock-out" of new and promising technologies that are not yet able to compete successfully in the energy markets against the established, conventional technologies based largely on burning fossil fuels.

2.2.7. Combining policy instruments

Since the above-described policy frameworks and instruments typically target a specific sustainability goal, it is important to examine the combined effects of several policy instruments, in order to identify potential synergies and/or trade-offs between them. A demonstration of cross-policy interaction in terms of environmental and cost impacts is particularly relevant for policy-makers in regions where different sustainability issues have different immediate importance. For example, the local air pollution in China or South Asia is of a greater concern for local governments than curbing greenhouse gases (GHG) emissions (Beg et al., 2002).

2.3. Sustainable energy scenarios

The implications of a portfolio of sustainable policies adopted over the reference development of energy system are explored through energy scenarios. Scenario-modelling results provide a basis for impact assessment of policy frameworks and help to analyse how the policy-invoked energy futures are compatible with sustainability goals, such as GHGs mitigation, reduction of dependency on fossil energy resources, reduction of air pollution, and the adoption of advanced energy supply and end-use technologies.

Beside the Baseline scenario that describes a reference development of the energy system, the following four groups of policy-driven scenarios are investigated in this study:

Group 1 – Climate-response policies - This policy framework adopts Kyoto-like (UNFCCC, 1999) scenarios for GHGs mitigation by forcing in the long term a “cap-and-trade” scheme across all world regions and all energy sectors to stabilise global CO_2 and non-CO_2 emissions. The mechanism for distributing emission permits among regions takes into account the needs and aims of economic development in non-Annex-B countries. Domestic policy instruments listed in Table 2 are not modelled individually, but they are assumed to be implicit to the emissions cap imposed on the regional energy systems. Furthermore, trading of emission permits across world-regions results in equalisation of the marginal cost of GHG-mitigation. The marginal cost of the global GHG constraint corresponds to a tax that would have to be levied to reach the specified emission reduction target. The set of scenarios within this group explores further implications of different flexibility mechanisms, i.e., allocation of the most efficient localities for GHG abatement ("where" flexibility), identification of the most efficient timing in emission reduction ("when" flexibility) and the most efficient mix of gases ("what" flexibility).

Group 2 - Policies to promote renewables - The second policy framework used in this analysis considers two domestic policy instruments: a renewable portfolio standard and production subsidies. First, scenarios are designed to address impacts of imposing an obligation to generate an exogenously determined, minimum amount of renewable electricity in all world regions. Trading of so-called "green certificates" between world regions is foreseen under this constraint of minimum renewable-electricity generation, wherein this trade would occur between regions having surpluses of renewable electricity and those having limited or expensive renewable-energy options for power generation. This policy element represents a kind of "cap-and-trade" policy that favours renewable resources. The second policy instrument modelled in this scenario group describes an incentive scheme comprising direct subsidies for electricity originating from renewable sources.

Group 3 - Internalisation of external costs to reduce air pollution - The first scenario within this group examines the implementation of policies that internalise the external costs of power generation related to local and regional air pollution (SO_2, NO_x, PM). External costs are estimated by applying the ExternE-Project costs determined for Europe (EC, 1999a) to all world regions, after adjusting costs for regional differences in population density, fuel quality, power-plant thermal efficiency and application of emissions-control systems. The second scenario internalizes external costs that comprise both air pollutants and emittants causing global climate change. Translated to the policy-making context, externality charges imposed on power generation is an approximation of an environmental tax levied to compensate for damages associated with emission releases.

Group 4 - Combined policy scenarios - Finally, in this group of scenarios the impacts of applying selected combinations of sustainable policy instruments within the policy portfolio discussed in Section 2.2 are examined. The following combinations of polices are modelled: CO_2-cap&trade + Renewable portfolio; CO_2-cap&trade + Local externality; Renewable portfolio + Local externality; CO_2-cap&trade + Local externality + Renewable portfolio. Table 6 gives a matrix of separate policy scenarios and combined policy scenarios, together with policy-related sustainability goals.

The successful implementation of sustainable energy policies discussed earlier requires substantial cost reduction and deployment of advanced generation technologies on the energy markets. All scenarios, therefore, assume policy actions in favour of investments in new energy technologies and allow for cost reductions associated with "learning-by-doing" (LBD) effects. At the same time, global technological learning spillovers and know-how transfer are foreseen. The role and implications of technology progress are analysed in the cases of the climate-response policies and renewable portfolio standard, and the results are contrasted with scenarios where endogenous technological learning (ETL) does not take place. The ETL concept and underlying assumptions are described further in Chapter 3. Finally, the methodology by which the policies are modelled and implemented into the scenarios is presented in detail in Chapters 5-9.

<table>
<tr><th colspan="6">Scenario sets</th><th colspan="4">Sustainability goal</th></tr>
<tr><th></th><th>Policy framework</th><th>/ Chapter</th><th colspan="2">Policy instrument</th><th>Scenario modalities</th><th>GHG mitigation</th><th>Reduced fossil fuel dependency</th><th>Decrease in air pollution</th><th>Improved access to advanced systems</th></tr>
<tr><td></td><td>Baseline</td><td>Chapter 4</td><td colspan="3">n.a.</td><td colspan="3">n.a.</td><td></td></tr>
<tr><td rowspan="17">Separate policy implementation</td><td rowspan="6">Climate response policies</td><td rowspan="4">Chapter 5</td><td colspan="2" rowspan="4">CO_2 cap & trade of emission permits, ETL</td><td>Where flexibility</td><td rowspan="6">√</td><td rowspan="6"></td><td rowspan="6"></td><td rowspan="3">√</td></tr>
<tr><td>Where + When flexibility</td></tr>
<tr><td>No-trade of emission permits</td></tr>
<tr><td>No-ETL</td><td>n.a.</td></tr>
<tr><td rowspan="2">Chapter 6</td><td colspan="2" rowspan="2">C-eq cap & trade of emission permits, ETL</td><td>Where + What flexibility</td><td rowspan="2">√</td></tr>
<tr><td>Where + What + When flexibility</td></tr>
<tr><td rowspan="5">Promotion of renewables</td><td rowspan="5">Chapter 7</td><td colspan="2" rowspan="3">Renewable portfolio standard, ETL</td><td>Trade of green certificates</td><td rowspan="5"></td><td rowspan="5">√</td><td rowspan="5"></td><td rowspan="2">√</td></tr>
<tr><td>No-Trade of green certificates</td></tr>
<tr><td>No-ETL</td><td>n.a.</td></tr>
<tr><td colspan="2" rowspan="2">Subsidy scheme, ETL</td><td>Trade of green certificates</td><td rowspan="2">√</td></tr>
<tr><td>No-Trade of green certificates</td></tr>
<tr><td rowspan="2">Reduction of air pollution</td><td rowspan="2">Chapter 8</td><td colspan="2" rowspan="2">Internalization of external cost in power generation, ETL</td><td>Local externality</td><td></td><td rowspan="2"></td><td rowspan="2">√</td><td rowspan="2">√</td></tr>
<tr><td>Local + global externality</td><td>√</td></tr>
<tr><td rowspan="4">Combined policy scenarios</td><td colspan="4">CO_2 cap & trade + Renewable portfolio, ETL</td><td rowspan="4">Chapter 9</td><td>√</td><td>√</td><td></td><td>√</td></tr>
<tr><td colspan="4">CO_2 cap & trade + Local externality, ETL</td><td>√</td><td></td><td>√</td><td>√</td></tr>
<tr><td colspan="4">Renewable portfolio + Local externality, ETL</td><td></td><td>√</td><td>√</td><td>√</td></tr>
<tr><td colspan="4">CO_2 cap & trade + Local externality + Renewable portfolio, ETL</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
</table>

Table 6. *Matrix of policy scenarios.*

3. Modelling framework

An effective assessment of energy-related policy instruments requires the use of models capable of simulating the technological change necessary to induce long-term, economic shifts towards a sustainable global energy system(s), while simultaneously representing in adequate detail key energy-economy-environment interactions.

The analysis presented in this thesis has been carried out using the latest version of the Global Multi-regional MARKAL Model (GMM) with endogenous technological learning (ETL) modelling capability, originally implemented by Barreto (2001) and applied at the Paul Scherrer Institut (PSI) for numerous energy policy analysis (e.g., Barreto and Kypreos, 2004; Rafaj et al., 2005b). MARKAL is a dynamic linear programming “bottom-up” model that finds the optimal development of the energy system in time under given technology characteristics and boundary conditions (Fishbone and Abilock, 1981). Since its initial development in the late 70s, the MARKAL model has become a widely applied tool for evaluating the impacts of policies imposed on the energy system of economy.

As for any other MARKAL (Market Allocation)-type modelling exercises, the GMM-based analyses and results reported herein should also be considered prospective, with emphases placed on the trends and insights resulting from driving forces determined by implementing the respective policy options.

3.1. MARKAL model and GMM features

The GMM model is part of the MARKAL family of models, which is a group of perfect-foresight, optimization energy-system models that represent current and potential future technology alternatives through the so-called Reference Energy System (RES). The MARKAL model is a generic technology-oriented model tailored by the input data to obtain the least-cost energy system configuration for a given time horizon under a set of assumptions about end-use demands, technologies and resource potentials. It represents the time evolution of a specific RES at the local, national, regional, or global level (IEA, 2005). Figure 3 gives a “top-level” depiction of the MARKAL energy flow and related technologies. The MARKAL models allow a wide flexibility in representation of energy supply and demand technologies and are typically used to examine the role of energy-technologies under specific policy constraints, e.g. CO_2 mitigation, local air pollution reduction, etc.

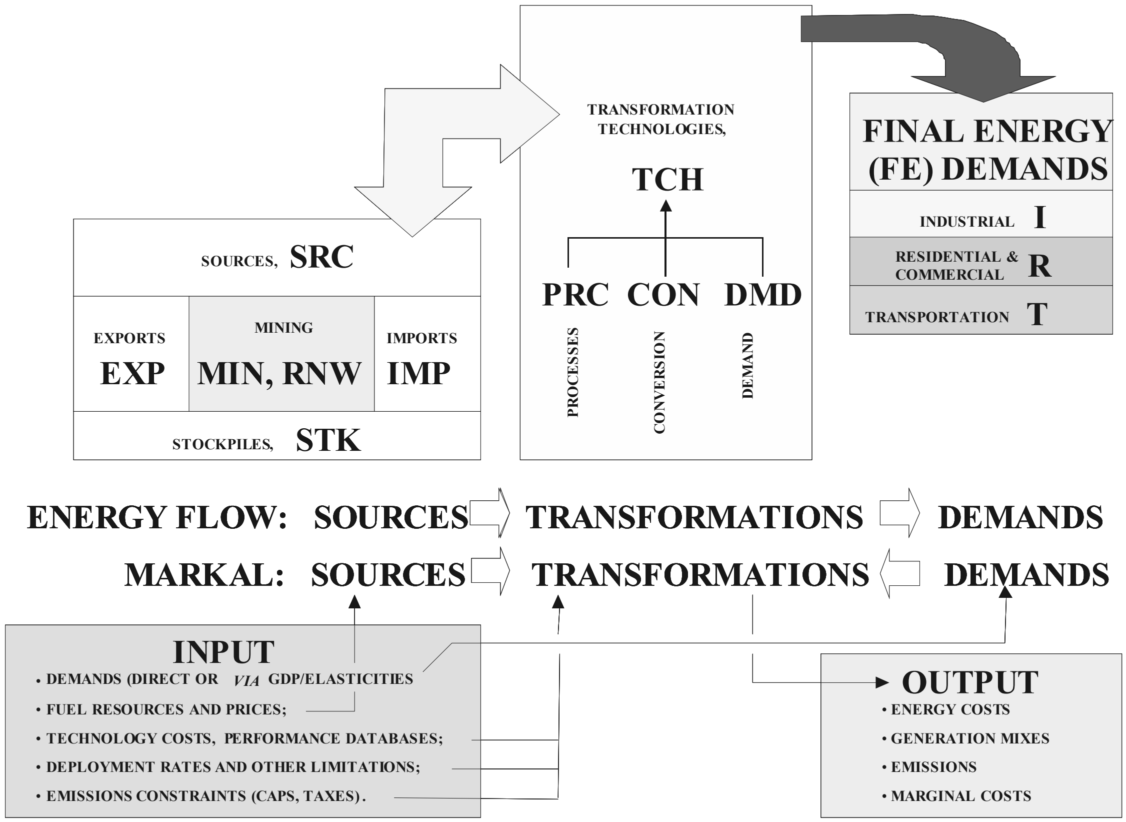

Figure 3.*"Top-level" energy flows within MARKAL (Fishbone and Abilock, 1981) showing the connectivity between sources, technologies, and demands, as well as typical input and outputs.*

The GMM version of MARKAL is an energy-system model representing the energy technology options on both demand and supply side of the complete energy system for five world regions. The details of mass and energy flows depicted for GMM at a "top level" in Figure 3 differ little from the basic MARKAL model described by Fishbone and Abilock (1981), and most recently by Loulou et al. (2004)[2]. In addition to the multi-regional characterization of global material and energy flows, important features of GMM include: a) Endogenous Technological Learning (ETL); b) Partial Equilibrium; and c) Trade between regions. In the order listed, a brief description on each of these three GMM capabilities is given separately in Sections 3.3-3.5.

The GMM model provides a relatively detailed representation of energy supply technologies and a stylized representation of end-use technologies. Technological details at a level that is sufficient for addressing policy questions needed to understand the development of new technologies and subsequent deployment is an important attribute of GMM.

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[2] This reference provides the official documentation of the standard MARKAL model including the full set of model equations and variables.

The five world regions described in GMM are shown in Figure 4. Three regions represent the industrialized countries: North America (NAME) and the remaining countries that as of 1990 belonged to the OECD and designated as OOECD, which comprises Western Europe and the Pacific countries having OECD membership (Japan, Australia and New Zealand); the economies-in-transition region combines the Former Soviet Union and Eastern Europe (EEFSU). Finally, the developing countries are grouped into the two remaining regions: developing Asian countries are included in the region ASIA, which is comprised of centrally planned Asia, India, South East Asia and Pacific Asia; the rest of the world is incorporated into the region LAFM, which includes Latin America, Africa and the Middle East.

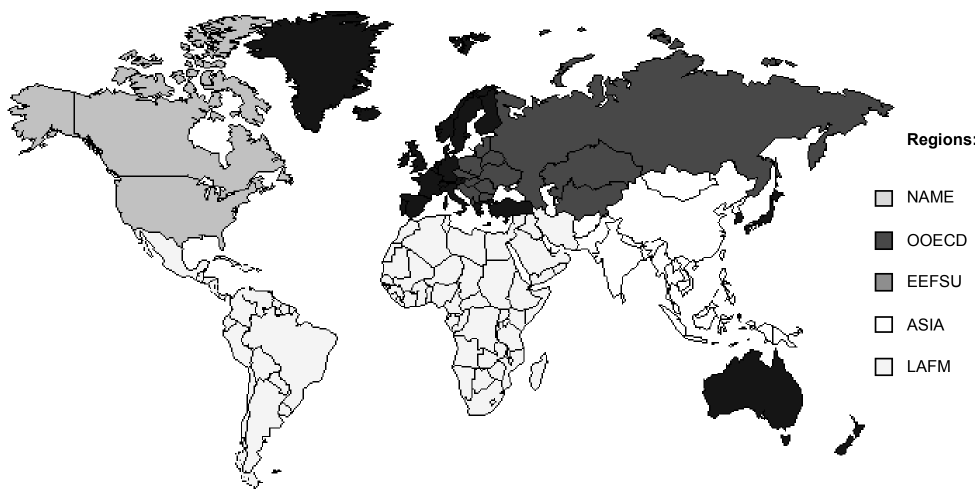

Figure 4. *Definition of the five world regions in the GMM model.*

The Reference Energy System (RES; Resource → Refining → Conversion → Final Energy → End-Use Energy) applied to each of the five GMM regions comprises all the possible energy chains that can be chosen by the model and is elaborated in Figure 5. Six end-use energy demand sectors are described in GMM, as is depicted in the right side of Figure 5. Industrial and residential-commercial sectors are divided according to thermal and electric (specific) energy uses, which accounts for four of the six end-use demand sectors. The transportation sector merges passenger and freight transport sub-sectors. Finally, the non-commercial use of biomass (i.e., fuel-wood and non-energy feedstock) is represented in the model.

A set of generic standard and advanced end-use devices is defined for each of the demand sectors, as is shown in Table 7. No explicit investment or fixed Operation and Maintenance (O&M) costs are considered for the generic end-use technologies specified in the model.

Instead, "inconvenience costs" are introduced to reflect the fact that as the historical trend of shifting towards more flexible and cleaner energy carriers continues at the final-energy level, some technologies may be more difficult or much less attractive to introduce. Substitution at this level, therefore, is driven mainly by efficiencies and fuel costs. Future penetration of end-use technologies is controlled by the introduction of exogenously controlled annual growth and declination rates and by the exogenous enforcement of an absolute bound on specific technologies to allow competition in the end-use markets.

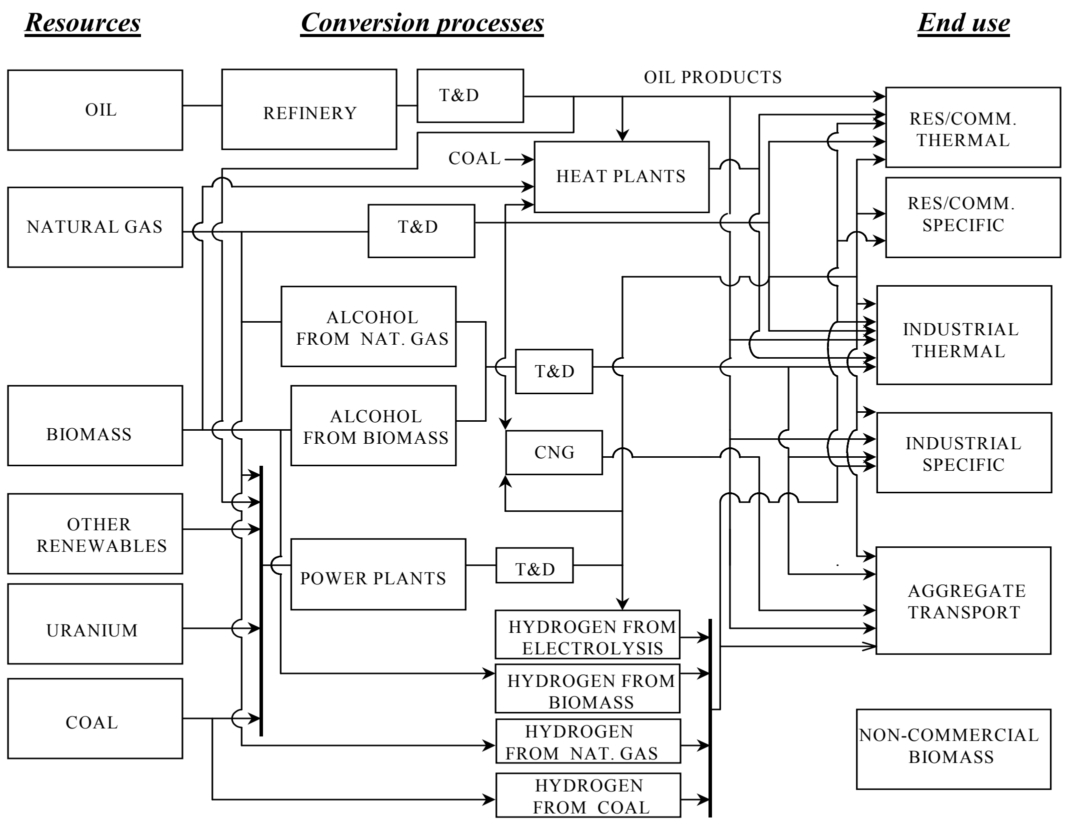

Figure 5. *Reference energy system (RES) applied in GMM.*

The time horizon modelled in GMM is 2000 to 2050, i.e., six periods of ten-years duration each, while a discount rate (*dr*) of 5% per annum is used in all calculations (see the discussion on the choice of discount rate in Section 9.3.1.). The version of GMM used herein considers energy-related GHG emissions of CO_2 and CH_4 at regional and global level, as contributed by each of the five regions described in Figure 4. In addition, CH_4 emissions from the waste management and N_2O emissions from industry are included; other sources of GHGs (e.g., cement and iron production, agriculture) are not modelled. Sulphur (SO_2) and nitrogen oxides (NO_x) emissions are represented only for the electricity generation sector.

Emission factors for electricity generation technologies and for other energy production processes are based on the IIASA-MESSAGE model database (Riahi and Roehrl, 2000), the Emission Database for Global Atmospheric Research (EDGAR) (Olivier and Berdowski, 2001) and the *ecoinvent 2000* database (Dones et al., 2004). The model is calibrated to reproduce energy statistics of the International Energy Agency (IEA) for the year 2000 (IEA, 2002a; IEA, 2002b). Additional information sources were used for calibration of installed power-generation capacities in 2000 (IEA, 2002d; IEA, 2002e; EIA, 2003b).

End-Use Demand Sectors					
Residential/ Commercial	Residential/ Commercial	Industrial	Industrial	Industrial	Transportation
Thermal	*Specific*	*Thermal*	*Specific*	*Feedstocks*	
Coal heating Oil heating Gas heating Electric heating Biomass heating District heating Methanol heating Hydrogen heating Electric heat pump Gas heat pump Hydrogen fuel cell Solar thermal	*Electric appliances Hydrogen fuel cell*	*Coal thermal Oil thermal Gas thermal Electric thermal Biomass thermal Process heat Methanol thermal Hydrogen thermal Electric heat pump Gas heat pump Hydrogen fuel cell Solar thermal*	*Electric specific Diesel specific Hydrogen repl. for diesel Methanol repl. for diesel Hydrogen fuel cell*	*Coal feedstock Diesel feedstock Natural gas feedstock Alcohol feedstock*	*Coal based trans. Oil based trans. Gas based trans. Electric-based trans. Alcohol based trans. Alcohol fuel cell Hydrogen fuel cell*
Price Elasticity (2010-2050)					
-0.25	*-0.20*	*-0.30*	*-0.20*	*-0.30*	*-0.30*

Table 7. *Generic end-use technologies applied in GMM; sector-specific price elasticities are indicated for each end-use demand category, see Section 3.4.*

3.2. Characteristics of the energy supply technologies

The supply sector and energy-conversion processes are represented with some detail in GMM. Technologies for the production of electricity, heat and a variety of final fuels (e.g., oil products, alcohol, methanol, hydrogen, natural gas) from several fossil and non-fossil sources are included, as well as the corresponding transport and distribution (T&D) chains. Investment, fixed O&M and variable O&M costs are specified for all supply technologies considered.

The technological and cost specifications of electricity generation technologies represented in GMM are listed in Table 8. All costs are given in US dollars for the year 2000. The data presented derives from various sources and literature reviews (e.g., Lako and Seebregts, 1998; EIA, 2003a; Wu et al., 2001, etc.). Characteristics of technologies with CO_2 removal are adopted from David and Herzog (2000) and IEA (2002f); additional CO_2-storage cost (10 \$/t-

CO_2 or 36.7 $/tC for every tonne captured) is charged for these technologies. This cost comprises expenditures for CO_2 transport, injection and disposal.

Levels of power generation based on renewable- and nuclear-energy sources are controlled in GMM through the imposition of exogenous bounds and annual growth or declination rates for each technology. Bounds applied for renewable resources reflect the regional technically achievable potential of each type of source and is provided by Riahi and Roehrl (2000); UNDP (2000); and IEA (2001b).

Technology	Start year	Life time	Load factor (max.)		Electric efficiency		Investment cost	Fixed O&M cost	Variable O&M cost
			start	2050	start	2050	$/kW	$/kW/yr	$/GJ
Fossil-fuel based power plants									
Coal conventional electric	2000	30	0.65	0.75	0.370	0.380	1050	38	0.72
Coal conventional electric with $DeSO_x/DeNO_x$	2000	30	0.65	0.75	0.360	0.370	1150	48	1.22
Coal conv. with $DeSO_x/DeNO_x$ and CO_2 seq	2010	30	0.65	0.75	0.296	0.304	2090	80	1.53
Coal cogeneration	2000	20	0.65	0.75	0.370	0.380	1155	49	1.5
Coal advanced electric (Supercritical, PFBC)	2000	30	0.65	0.8	0.429	0.500	1584	47.5	0.75
Coal advanced electric with CO_2 seq	2010	30	0.65	0.8	0.365	0.425	2060	90	1.13
Integrated Coal-Gasification Combined Cycle (IGCC)	2000	30	0.85	0.85	0.425	0.500	1401	40	0.88
Coal IGCC with CO_2 seq	2010	30	0.85	0.85	0.361	0.425	1910	52	1.23
Natural Gas Combined Cycle (NGCC)	2000	20	0.65	0.75	0.510	0.588	560	36.6	0.63
NGCC with CO_2 sequestration	2010	20	0.65	0.75	0.459	0.529	1015	60	0.88
Gas turbine	2000	20	0.2	0.2	0.360	0.360	350	58.5	0.51
Gas steam conventional	2000	20	0.65	0.65	0.333	0.410	987.7	50.6	0.56
Cogenaration gas turbine	2000	20	0.4	0.46	0.370	0.370	750	51.6	0.63
Gas fuel cell (GFC)	2000	20	0.65	0.65	0.599	0.649	2463	43.5	0.63
Hydrogen fuel cell (CHP) in industry (H_2FC)	2010	20	0.85	0.9	0.4	0.6	3500	20	7.5
Hydrogen fuel cell (CHP) in res&com. (H_2FC)	2010	20	0.85	0.9	0.4	0.5	3500	20	5.8
Oil electric	2000	20	0.65	0.8	0.303	0.400	991	63.6	0.57
Nuclear and renewable power plants									
Nuclear plant - Light Water Reactor (LWR)	2000	30	0.8	0.9	0.327	0.327	1800	90	2.19
Advanced new nuclear power plant (NNU)	2010	30	0.85	0.9	0.345	0.345	1900	70	1.19
Hydro-electric plant (small and large)	2000	50	0.45	0.46	0.385	0.471	2850	49.5	0.12
Solar photovoltaics (SPV)	2000	20	0.2	0.25	0.400	0.400	5000	9	1.25
Solar thermal electric	2000	20	0.2	0.2	0.400	0.400	2900	9	1.25
Wind turbine	2000	20	0.3	0.3	0.330	0.330	1150	13.5	0.83
Biomass power plant	2000	20	0.75	0.75	0.333	0.333	2650	47.8	0.92
Geothermal electric	2000	20	0.75	0.75	0.381	0.381	2900	28	0.9

Table 8. *Cost and performance of power generation technologies in the GMM model.*

As is indicated in Table 9, except for hydropower, only upper bounds are applied in 2050 for renewable power generation; the level of actual generation, therefore, is not forced, but is left free for determination through competition. Power-network stability aspects are taken into account by assuming a maximum penetration fraction of intermittent power generation (e.g., wind power, solar photovoltaic) of 25% of total electricity production.

In the case of nuclear power, the lower bound in 2050 corresponds to the present global level of generation. No limit is provided for CO_2 that can be stored in any kind of reservoir. The level of carbon sequestration, however, is controlled by annual growth rates of technologies being operated with CO_2 emissions removal.

Bounds for renewable electricity sources in 2050 (EJ)						
Regions:	NAME	OOECD	EEFSU	ASIA	LAFM	WORLD
Hydro max	2.8	3.4	5.8	7.6	8.5	28.1
Hydro min	2.2	2.0	1.1	1.2	2.4	8.9
Wind max	9.4	12.0	9.3	9.9	9.8	50.4
Solar PV max	3.6	2.2	1.6	14.6	5.2	27.3
Biomass max*	8.4	3.3	10.8	53.5	112.4	188.4
Geothermal max	1.0	0.8	2.0	5.0	2.0	10.8
Bounds for nuclear power in 2050 (EJ)						
Nuclear max	18.0	18.0	9.5	20.0	18.0	83.5
Nuclear min	2.0	2.9	0.9	1.5	0.1	7.4

Table 9. *Assumptions for renewable and nuclear electricity sources applied in GMM.* Biomass potential refers to both electricity and heat production.*

3.3. Endogenous technological learning

The GMM model addresses technology dynamics in energy-systems models, and focuses on understandings the impacts of ETL, which can be a key driving force behind technological progress (Messner, 1997). A typical learning curve describes the decrease in the specific (unit) cost of a given technology as a function of the cumulative installed capacity, which serves as a proxy for the accumulated experience. This approach reflects the fact that some technologies can experience declining unit costs because of the process of 'learning-by-doing' (LBD). ETL enables analysis of the way in which respective technology enters the energy market through learning-induced unit-cost reductions.

The specific costs SC_{jt} of a technology j can be reduced in a period t as a result of the accumulation of experience approximated by the term $\left[\frac{\mathrm{CC_{jt}}}{\mathrm{CC_{j0}}}\right]^{-\beta_j}$; CC_{jt} is the cumulative capacity in t; CC_{j0} is the initial cumulative capacity; β_j is the learning index.

$$SC_{jt} = SC_{j0} \cdot \left[\frac{CC_{jt}}{CC_{j0}}\right]^{-\beta_j} \text{, where } SC_{j0} \text{ is the initial specific cost.} \tag{1}$$

$$\beta_j = \frac{\ln(1 - LR_j)}{\ln 2} \text{, where } LR_j \text{ is the learning rate.} \tag{2}$$

The learning rate (LR) is defined as the relative decrease in specific investment cost upon doubling of the installed cumulative capacity, i.e., a learning rate of 20% implies that the costs are reduced by 20% relative to the initial value each time when the cumulative capacity is doubled.

Learning spillovers across technology clusters are not modelled in GMM. Instead, spatial knowledge spillovers of separate learning technologies across world regions are assumed to take place. A detailed description and mathematical formulation of the 'learning-by-doing' (LBD) modelling approach applied in GMM can be found in Barreto and Kypreos (2002).

In the version of the GMM model used in this analysis, technology learning is endogenized only for the investment costs of selected electricity generation technologies, as is summarized in Table 10 together with the corresponding learning rates (LR) and initial specific investment costs. The learning rates assumed are within the ranges reported in the literature (McDonald and Schrattenholzer, 2001). The "Floor" cost represents an exogenously specified lower bound to hinder the possibility of further cost reduction for a given technology in its (expected) maturity stage. A higher value of LR for technologies with CO_2-capture is based on an assumption that the CO_2-capture device applied to the reference power plant might contribute to the "learning" potential of a reference plant. Technologies equipped with CO_2-capture, therefore, could undergo a stronger cost reduction.

Technology	Learning Rate (%)	Initial Specific Investment Cost (US$_{2000}$/kW)	Floor cost (US$_{2000}$/kW)
Hydrogen Fuel Cell	18	3500	300
Advanced Coal Plant	6	1584	500
Advanced Coal Plant with CO_2 capture	7	2060	500
IGCC	6	1401	500
IGCC with CO_2 capture	7	1910	500
Advanced New Nuclear Power Plant	4	1900	800
NGCC	10	560	300
NGCC with CO_2 capture	10	1015	300
Gas Fuel Cell	18	2463	500
Solar Photovoltaics	19	5000	1000
Wind Turbine	10	1150	500

Table 10. *Electricity generation technologies for which technology learning is endogenized in GMM.*

3.4. Partial equilibrium and elastic end-use demands

The objective of a simple least-cost energy-system model is typically the minimisation of the total cost of satisfying exogenously specified levels of energy services. If the energy service demands are completely inelastic, the model is not able to capture the consumers price-induced feedback invoked from a given policy constraint. From the policy-making perspective it is desirable that a modelling tool used for the policy assessment computes both the flows and prices of energy commodities so that the amount of energy supplies corresponds to the amounts the consumer would be willing to buy (Loulou et al., 2004). The GMM version used for this analysis, therefore, applies the ETL option in combination with a partial-equilibrium algorithm (Loulou and Lavigne, 1996) that adjusts demands for energy services for changes (increases) in marginal cost of services that results from the imposition of a given policy constraint, as is described below.

The partial equilibrium MARKAL model with elastic demands (referred to as the MARKAL-ED) makes use of a procedure whereby the energy end-use demands that drive GMM are not fixed, but instead are elastic to their own prices; these prices are endogenously computed by the model in the Baseline case. The price elasticity of demand sectors represented in GMM is given in Table 7. The end-use demands are self-adjusted if modifications related to a given non-Baseline scenario affect prices. This procedure is illustrated graphically in Figure 6. The model attains partial equilibrium for energy markets when the sum of producer and consumer surpluses is maximised. Consequently, the model objective function is comprised of two terms: a) the energy/technology production costs; and b) the loss of consumer welfare associated with demand reduction (Kanudia and Loulou, 1999). Further details on partial-equilibrium properties and its implementation in the MARKAL-ED model can be found in Kypreos and Cadena (1998), and in Loulou et al. (2004). In what follows, the objective function of the GMM model is itemised based on Kypreos (1996) and Loulou et al. (2004).

The objective of the MARKAL model with ED, such as GMM, is to minimize the total cumulative cost of the energy system, i.e., the objective function (*Z*). The objective function is composed of three basic elements: Investment cost (*INVC*) in technologies (*j*), Annual cost (*ANC*), which includes also the Welfare loss resulting from reduced end-use demands (*DEML*). The objective function also accounts for the salvage cost (*SALC*) for all assets stranded at the end of the horizon. The investment cost is calculated as follows:

$$INVC_t = \sum_{r,j} INV_{t,r,j} * SC_{t,r,j} \qquad (3)$$

where *INV* is the new capacity addition for technology *j*, in period *t*, in region *r*, and *SC* is the specific investment cost.

In each period, the investment costs are first annualized, before being added to the other costs to obtain the annual cost in each period. The model then computes a total net present value of all annual costs (*ANC*), discounted to the reference year (2000), as explained below. This quantity is minimized by the model over all regions *r*, all technologies *j*, all demand sectors *d*, all pollutants *p*, and all fuels *f* to compute the equilibrium.

The Annual cost (*ANC*) can be decomposed into the following elements: Annualized investment cost (*AINVC*) in technologies (*j*); Fixed and variable annual Operation and Maintenance (*O&M*) costs (*FIXOM, VAROM*) of technologies (*j*); Fuel delivery costs (*DELC*); The unit transport or transaction cost (*TRDC*); Cost of exogenous energy imports (*IMPC*) and domestic resource production (*PRDC*); Revenue from exogenous energy exports (*EXPC*); Welfare loss due to reduced end-use demands (*DEML*); Taxes and subsidies associated with energy sources, technologies, and emissions (*TAX*). The Annual cost (*ANC*) can be then expressed as follows:

$$
\begin{aligned}
ANC_t = & \sum_{r,j} \left\{ \begin{array}{l} AINVC_{t,r,j} * INV_{t,r,j} \\ + FIXOM_{t,r,j} * CAP_{t,r,j} \\ + VAROM_{t,r,j} * ACT_{t,r,j} \\ + \sum_{f} \left[DELC_{t,r,j,f} * INP_{t,r,j,f} * ACT_{t,r,j,f} \right] \end{array} \right\} \\
& + \sum_{r,f} \left\{ \begin{array}{l} PRDC_{t,r,f,l} * MIN_{t,r,f,l} \\ + TRDC_{t,r,f} * TRD_{t,r,f} \\ + IMPC_{t,r,f,l} * IMP_{t,r,f,l} \\ + EXPC_{t,r,f,l} * EXP_{t,r,f,l} \end{array} \right\} \\
& + \sum_{r,p} \left\{ TAX_{t,r,p} * ENV_{t,r,p} \right\} \\
& + \sum_{r,d} \left\{ DEML_{t,r,d} \right\}
\end{aligned} \tag{4}
$$

where:

$CAP_{(t,r,j)}$ = installed capacity of technology *j*, in period *t*, in region *r*;

$ACT_{(t,r,j)}$ = activity level of technology *j*, in period *t*, in region *r*;

$INP_{(t,r,j,f)}$ = the amount of commodity (or fuel) *f* required to operate one unit of technology *j*, in period *t*, in region *r*;

$MIN_{(t,r,f,l)}$ = quantity of commodity *f* extracted in region *r* at price level *l* in period *t*;

$TRD_{(t,r,f)}$ = quantity of commodity *f* traded among regions *r* in period *t*;

$IMP_{(t,r,f,l)}$, $EXP_{(t,r,f,l)}$ = quantity of commodity *f*, price level *l*, imported or exported by region *r* in period *t*;

$ENV_{(r,t,p)}$ = Emission of pollutant *p* in period *t* in region *r*.

The objective function Z is the discounted sum of its elements, discounted over the planning horizon. Different discounting applies to the Investment cost (*INVC*) and to the Annual cost (*ANC*). The Annual cost is first discounted to the beginning of the period (t) using the discounting factor Df_0, and thereafter to the reference year, by Df_t:

$$Z = \sum_{t,r} INVC_{t,r} * Df_t - \sum_{t,r} SALC_{t,r} * Df_t + \sum_{t,r} ANC_{t,r} * Df_t * Df_0 \, , \tag{5}$$

while

$$Df_t = (1+dr)^{-ypp*(t-1)} \text{, and } Df_0 = \sum_{k=0}^{k=ypp-1} (1+dr)^{-k} \, , \tag{6}$$

where *ypp* are years per period t, and *dr* is the discount rate.

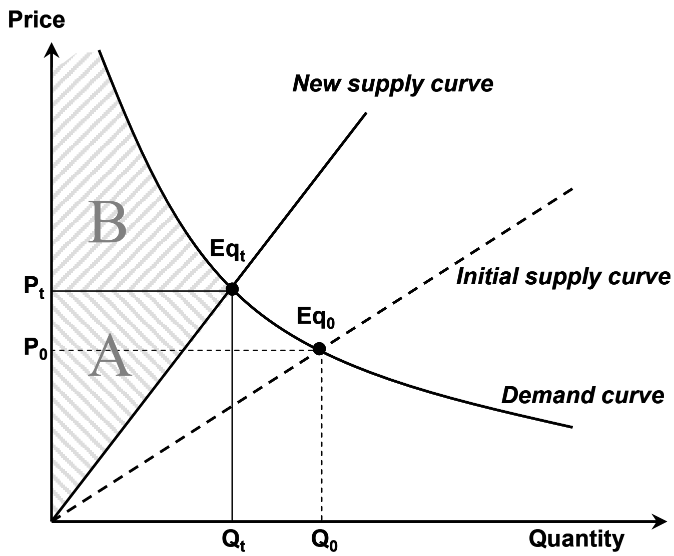

Figure 6. *Illustration of partial equilibrium between demand and supply, adopted from Kypreos and Cadena (1998). Eq_0 is the initial equilibrium (defined by initial demand Q_0 and initial price P_0). A policy constraint will increase the cost of supply (e.g., electricity) and the new equilibrium price moves to P_t. Equilibrium is shifted to the point Eq_t (defined by new demand Q_t and new price P_t). The equilibrium is found, when the area composed by producer surplus (A) and consumer surplus (B) is maximised.*

The GMM model with elastic demands does not capture the entire macroeconomic feedback associated with energy-policy instruments applied. To do so would require coupling of GMM with a macro-economic model, (e.g., the MACRO module) for adjusting other macroeconomic variables (Kypreos, 1996). These considerations are important for a proper interpretation of the total system costs results provided by GMM. For instance, internalisation of externalities results in allocation of resources through the integration of externalities in energy prices. Although not modelled explicitly within this study, in a “real-world” situation the extra charge or a tax imposed on the energy system is exptect to be recycled back into economy and used for different purposes.

3.5. Trade between regions

The multi-regional feature of GMM allows simulation of bi-lateral and global trade of selected energy or environmental commodities (e.g., fuels, electricity, emission permits). Global trade of any given commodity must balance at each period (i.e., the sum of trade variables over all regions is equal to zero). The quantities as well as the unit cost (corresponding to the marginal price) of an endogenously traded commodity are model results. Shadow price related to the commodity globally traded among regions reflects the cost the energy system must pay for a unit of trade. A zero value of the shadow price implies that no cost is associated with producing and delivering the commodity, which is highly unlikely (EIA, 2003b).

In GMM, the inter-regional trading of hard coal, natural gas, liquefied natural gas, oil and oil products is modelled. In the scenarios reported herein, electricity is not traded among regions or intra-regionally. Depending on the scenario and policy framework modelled, other commodities that can be traded comprise CO_2-emission permits, Carbon equivalent emission permits, and green electricity certificates.

Allowing for global trade of a given commodity, the trade variables transform the five regional modules of GMM into a single global energy model where actions taken in one region may affect all other regions. For instance, if regional carbon emission constraints are imposed on the energy system, CO_2-emission trading facilitates the reallocation of the carbon reduction targets within the trading regime and, therefore, creates incentives to deploy low-carbon technologies among the regions participating in the trading regime (Barreto and Kypreos, 2004).

Again, the marginal costs of carbon emissions reduction (e.g., a shadow price of carbon-emission permits globally traded), which is determined endogenously by the GMM model, are equalised across the regions, and the revenue from exports received by the exporting region is exactly cancelled by the cost of imports incurred by the importing region. Cost and revenues resulting from the permit trade for each region, however, can be calculated *ex post*. Transaction costs and other additional charges possibly associated with trading of emission permits, however, are not accounted in this analysis.

4. Defining Baseline scenario and basic assumptions

The set of policy instruments analysed in this work is applied on a Baseline development scenario (or a reference scenario/case) based on the B2 scenario reported by IPCC (2000) in the Special Report on Emission Scenarios (SRES) and described in details in Riahi and Roehrl (2000). The B2 scenario is a "dynamics-as-usual" scenario describing a plausible development of the global energy system, 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 with time.

The baseline end-use demands and renewable-energy potentials are directly taken from the B2 scenario, and availability of fossil fuels is adopted from Rogner (1997). No attempt has been undertaken, however, to match the Baseline scenario with the results of the SRES-B2 scenario. In this respect, the reference development reported herein corresponds to a PSI scenario, since the allocation of resources is based on an optimisation performed under conditions of perfect foresight with LBD considerations included. In addition, global spillovers of experience and knowledge transfer (including from North to South) are assumed to take place.

The B2 storyline envisages a given degree of increased concern for environmental and social aspects and is consistent with current institutional frameworks and current technology dynamics. Population growth is consistent with the United Nations median projection for population growth, which is projected to increase to 9.4 billion people by the year 2050, and follows a continuation of historical trends. As shown in Figure 7, economic growth is gradual, with the world gross domestic product (GDP) increasing at an average rate of 2.8% per annum between 2000 and 2050. Income per-capita is projected to grow at a globally average rate of 1.8% per year for the same period, which translates into an average value of 11,700$$_{(1990)}$ per capita in the year 2050 at market-exchange rates (mex).

On the demand-side it is assumed that the historical shifts from non-commercial to commercial fuels and towards cleaner and flexible, grid-transported energy carriers at the final-energy level continue into the future. It is assumed that non-energy feedstocks (i.e., mainly oil products and to a much lower extent natural gas and coal) can be replaced by alcohol feedstocks after 2020. Conservation measures are not explicitly modelled. In the original B2 scenario, assumptions concerning energy-intensity and energy-demand projections for each region and demand category are formulated according to trend extrapolations of past performance based on autonomously (e.g., not related to price) declining energy intensity together with considerations of regional income and price elasticities.

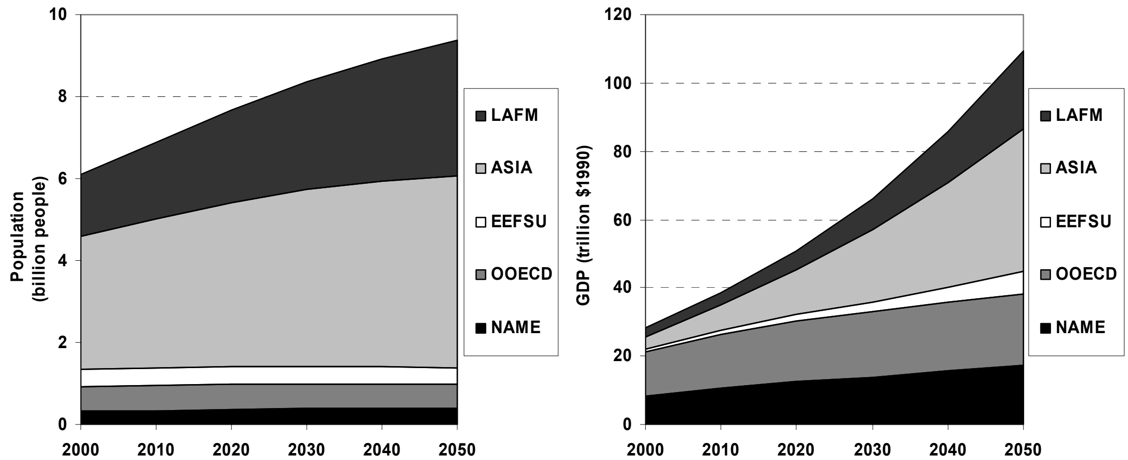

Figure 7. *Time dependence of population and gross domestic product (GDP) per region in the illustrative B2 scenario. Source: IPCC (2000).*

The policy assumptions applied in the Baseline scenario include some expectations regarding climate response policy. Considering recent efforts to implement the Kyoto protocol in the Annex B countries, some representation of climate policy is included in the Baseline scenario for the OOECD region, wherein a generic carbon tax of 10 $\$_{(2000)}$/tonne CO_2, starting from the period 2010 and held constant over time, is adopted. Another important aspect that distinguishes the Baseline scenario from the SRES-B2 scenario is that in the Baseline scenario the explicit long-term SO_2-control policies are not adopted in the industrialized and developing regions. Nevertheless, it is assumed that the specific emission factors for SO_2 and NO_x emissions for power plants in developing regions will improve and gradually achieve the standards of the OECD region by 2050.

Time evolution and regional distribution of CO_2 and SO_2 emissions in the reference development are summarised in Figure 8. Total global energy-related carbon emission rates in the Baseline scenario increase continuously from the present level of 6.3 GtC/yr throughout the time horizon modelled, giving an annual rate of 1.97 %/yr and reaching a level of 16.8 GtC/yr by the year 2050. The SO_2 emissions from the power generation sector peak in the period 2030-2040 at the rate of 104 Mt SO_2 per year, with region of ASIA being the main contributor.

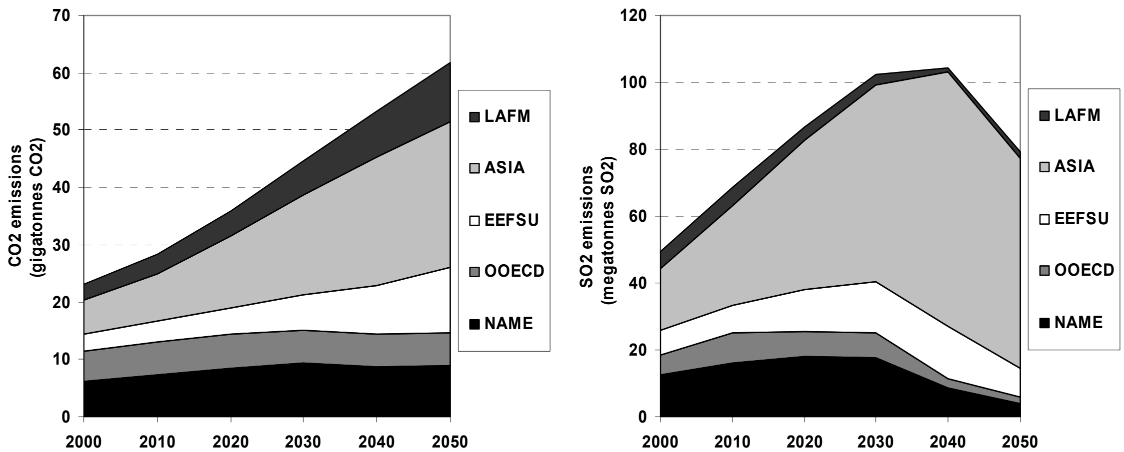

Figure 8. *Energy-related CO_2 and SO_2 emissions in the Baseline scenario. SO_2 emissions refer only to the emissions from the power generation sector.*

Under the Baseline scenario, global primary energy consumption experiences a significant increase over the time horizon and is largely dominated by fossil fuels, as is indicated by Figure 9. Use of both coal and natural gas grows substantially, with clean-coal technology and natural gas becoming the predominant sources of electricity by 2050. Growth of oil demand remains modest (1.1% per annum), but continues to make a significant contribution to primary-energy demand. Non-fossil resources, i.e., nuclear and renewable energy, slowly gain market share[3].

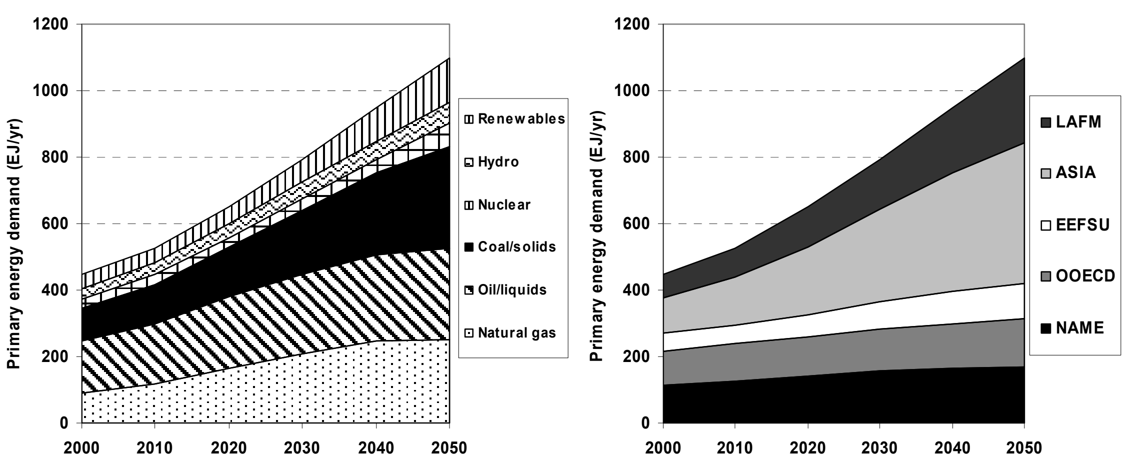

Figure 9. *Global primary energy demand by fuel and by region in the Baseline scenario.*

[3] The fossil-fuel equivalent for these non-fossil sources is taken as the reciprocal of the average efficiency of the fossil fuel power plants, and is used for reporting the primary-energy equivalent of renewable and nuclear energy production of electricity. A fossil equivalent of 3.033 is used in GMM.

Electricity generation undergoes a vigorous growth in the Baseline scenario, with the bulk of this growth being driven by developing regions and by 2050 reaching levels by 4.4 times higher than in the year 2000. Coal-fired power plants dominate the electricity market and contribute by 50% of the total global power generation at the end of the time horizon (2050). From the period around 2030, the conventional coal plants are replaced by advanced coal-based systems, i.e., supercritical plants, Pressurized Fluidised-Bed Combustion (PFBC), and Integrated Coal Gasification Combined Cycle (IGCC), which are subject to technological learning. The second most competitive system in 2050 is the natural gas combined cycle (NGCC), which contributes more than 20% of total power production. The fossil-fuelled plants with CO_2-capture do not penetrate the market in the Baseline.

The contribution from nuclear power does not grow substantially for the Baseline conditions, but a substitution of conventional plants by new reactor designs occurs. While the power generation from wind turbines experiences significant growth worldwide, the amount of hydroelectric production grows only slightly. Solar-photovoltaic technology remains in essence "locked-out". As is shown in Figure 10, approximately one fourth of the electric power in the Baseline is supplied by the carbon-free nuclear- and renewable-energy sources in the year 2050. It should be emphasised that the significant penetration of some of the advanced “learning” technologies in the Baseline scenario is not autonomous, but is related to the specific assumptions about energy-technology dynamics. An increased market share and associated cost reductions due to LBD-effects will not occur without policies supporting deployment of advanced generation systems.

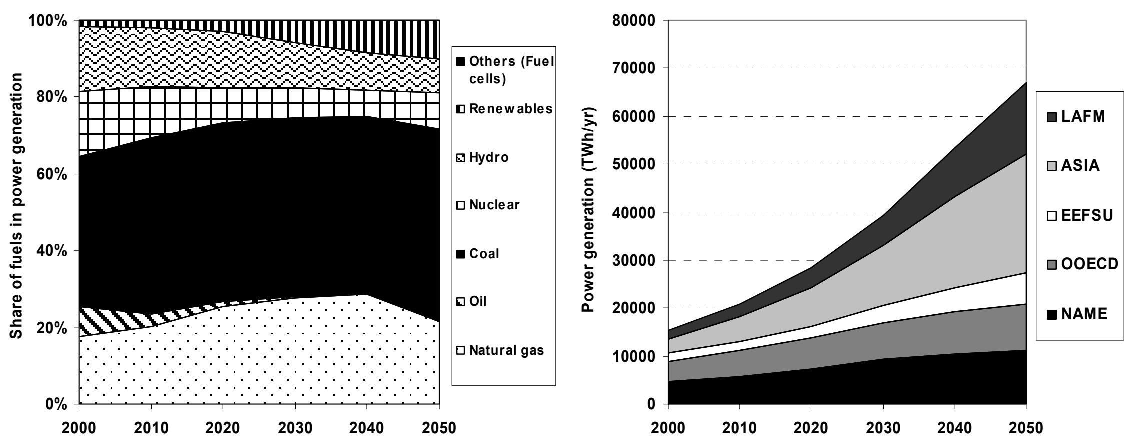

Figure 10. *Development in global electricity production by fuel (relative shares) and by region in the Baseline scenario.*

The time evolution of parameters discussed above for the Baseline case represents the key driving forces for the present and future sustainability impacts of the global energy system. Interaction of these drivers is highly complex and can not be fully described by the "bottom-up" GMM model. A brief discussion is provided here, however, to illuminate links from socio-economic drivers (i.e., population and GDP) to technology drivers (i.e., energy resource use and technological progress), and associated environmental impacts in the reference development of the Baseline scenario.

In general, the sustainability impacts of the energy system can be decomposed through the so-called IPAT identity (IPCC, 2000) as follows:

$$\underline{I}MPACT = \underline{P}OPULATION * \underline{A}FFLUENCE * \underline{T}ECHNOLOGY \tag{7}$$

The IPAT identity suggests that the impacts, e.g., emission levels, are determined by the population levels times income per capita times the level of technology deployed. The IPAT identity can be decomposed further and applied to analyses of energy-related emittants, e.g., CO_2 or SO_2, although the driving forces might have different weight and can be organized differently, depending on the species of anthropogenic emissions under examination. A frequently used approach to formulate the decomposition of CO_2 emissions is based on the Kaya identity (Kaya, 1990; IPCC, 2000):

$$CO_2 = Population \cdot \left(\frac{GDP}{Population} \right) \cdot \left(\frac{PE}{GDP} \right) \cdot \left(\frac{CO_2}{PE} \right) \tag{8}$$

where the CO_2 emissions level is the product of population; income per capita; energy intensity defined as the primary energy (PE) consumed per a unit of GDP produced; and finally carbon intensity describing the CO_2 emissions per unit of PE used.

The long-term relationships between global energy and socio-economic development in the Baseline scenario are summarised in Figure 11. The income per capita increases by a factor of 2.5 in 2050 relative to the base year 2000 and is associated with an increase in the per-capita primary-energy consumption by a factor of 1.6. The right-hand-side of the same figure shows that the primary energy consumption grows in all regions over the time horizon. Large differences between industrialized and developing regions, however, remain since no explicit policy actions to increase equity take place. Simultaneously, the energy intensity decreases considerably in the developing regions and in the transition countries of EEFSU, suggesting an improved efficiency in the energy use per unit of economic activity. Global primary energy intensity in 2050 drops by 37% as compared to 2000.

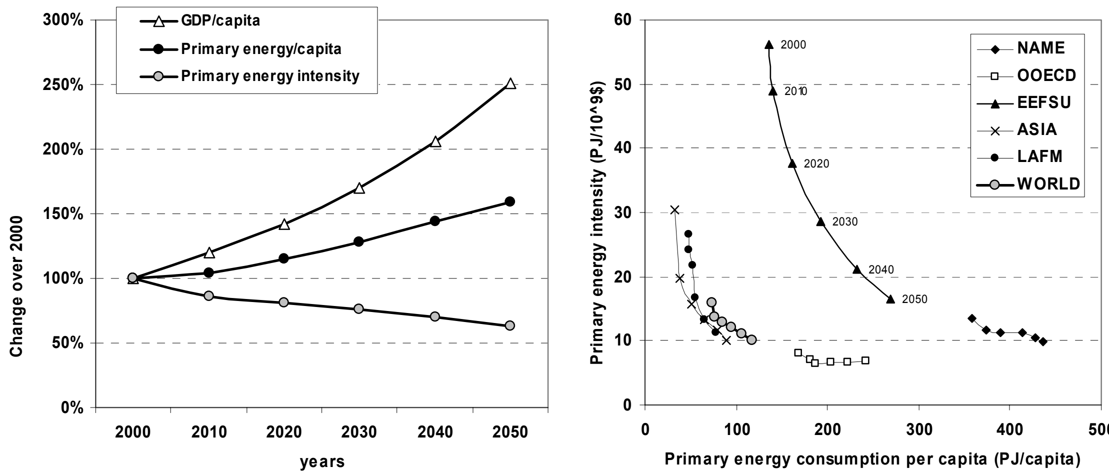

Figure 11. *Change in the global GDP/capita and PE/capita relative to the levels in the year 2000, and the time evolution of the primary energy intensities as a function of PE/capita by region in the Baseline scenario.*

The Baseline global energy-related CO_2 emissions are projected to increase by 170% in the end of the time horizon as compared to the present levels. A substantial rise in the consumption of carbon-intensive fuels, particularly coal in the developing world, results in the per-capita CO_2 emissions that are by 75% higher than in the year 2000. As depicted in Figure 12, the fastest growth in this indicator is reported for the regions of ASIA and EEFSU, while the values remain almost constant for OOECD and even decrease in NAME after 2030.

Time evolution of carbon intensity reflects the relation of CO_2 emissions with the primary energy consumption. It is remarkable that despite increasing contribution of fossil fuels to meeting the primary-energy demand over the time horizon, the growth in the global carbon intensity remains modest. Changes in carbon intensity are more pronounced at the regional level where a decreasing trend is observed after 2030. This result also indicates the growing importance of advanced (i.e., less carbon-intensive) supply technologies deployed in the global energy markets as the global per-capita GDP grows.

Finally, the 'CO_2-emissions per unit of GDP' indicator decreases over the horizon by 30% relative to 2000, with ASIA and EEFSU being the main contributors to the global reduction levels. Nevertheless, an interpretation of this indicator would be somewhat more speculative, since besides technological progress and fuel-switching, it is driven by structural shifts in different economy sectors, e.g., from industry and manufacturing to services.

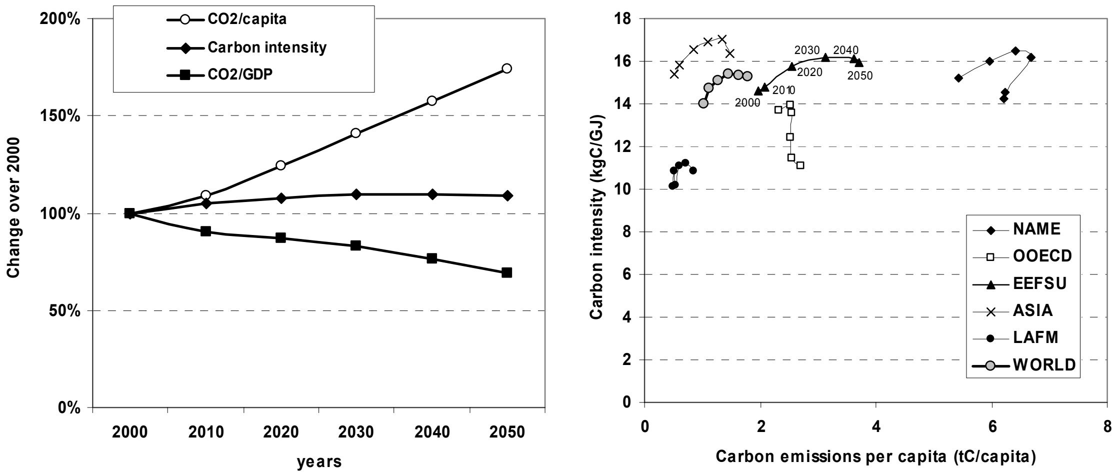

Figure 12. *Change in the global CO_2/capita and CO_2/GDP relative to 2000, and the time evolution of carbon intensities as a function of CO_2/capita by region in the Baseline scenario.*

From the discussion above it is apparent that a number of drivers determine the sustainability performance of the global energy system. These drivers can be influenced by different policies to achieve compliance with key elements of sustainable development, as is outlined in Chapter 2. Implementation of policies aimed at the socio-economic drivers, i.e., population growth or per-capita income, might result in uncovering important ethical and equity issues. Moreover, socio-economic determinants are exogenous in the GMM model and are not addressed in this work. On the other hand, it is both relevant and feasible to study impacts of policies addressing the technology-related drivers, e.g., energy and carbon intensity or the deployment of advanced energy technologies.

Based on the global CO_2 emission trajectory for the non-global-policy reference development provided in Figure 8 and considering the climate impacts of similar carbon emission paths reported by IPCC (2001b), the atmospheric CO_2 concentrations might increase in the long term, under the Baseline scenario reported herein, from about 365 ppmv in 2000 to a level around 750 ppmv in 2100. Implications of flexible climate-response policies that are targeted at the long-run stabilisation of the anthropogenic CO_2 emissions at the concentration levels about 550 ppmv, are analysed in the following chapter.

5. International flexible policies for CO_2-mitigation

This chapter explores the advantages of international climate response policies that could enhance the flexibility of CO_2 mitigation. Among other reasons, flexible mitigation policies are required because of the large technological inertia of the global energy system, which causes structural transitions to span long time periods. In addition, large institutional inertia and political obstacles inhibit the rapid implementation of climate-change policies (IEA, 2002g). For these reasons, the role of spatial, temporal and technology-related *flexibility* in implementing CO_2-mitigation policies in the global energy system is investigated.

The results presented here are drawn mainly from Rafaj et al. (2005a) and Rafaj et al. (2005b). The analyses focus on energy-related CO_2 emissions, which represent a substantial share of present-day anthropogenic greenhouse gas (GHG) emissions. Using the GMM model, a range of CO_2-reduction strategies is examined and the resulting costs of CO_2 reduction are compared across several policy-related scenarios. In addition, the impacts of endogenizing technology learning (ETL) on the electricity sector in determining technology choices and CO_2 abatement policies are analysed. Specifically, the induced changes in the primary-energy supply and the electricity-generation technology mix, the modified rates of CO_2 emissions, and the diffusion of advanced technologies in energy and end-use markets are described.

A first relevant aspect refers to the so-called "where" flexibility of CO_2 mitigation. Flexibility mechanisms, as defined by the Kyoto protocol (UNFCCC, 1999), are basically methods of GHG emissions trading that allow a country to utilize the least-cost emissions reduction options. These flexible mechanisms are categorized as Joint Implementation (JI), the Clean Development Mechanism (CDM) and International Emissions Trading (IET), all of which are designed to allow industrialised countries with limited domestic low-cost emission-abatement possibilities to reduce mitigation costs by investing in emissions-reducing projects, or in carbon permits purchase, in other countries and thereby acquire credits that equal the costs of avoided GHG emissions (Sager, 2003b). Taking advantage of the "where" flexibility of mitigation, these mechanisms can contribute to achieving cost-efficient emissions reductions. For modelling purposes, this analysis considers a generic carbon-emission trading mechanism, which refers to all emission-permit trading and does not distinguish between the specifics of the IET, JI, and CDM categories considered under the Kyoto protocol. Hence, specific features associated with each of the Kyoto mechanisms are not considered here.

Another important kind of policy flexibility addressed herein is the “when” flexibility, which allows for an optimal trajectory of emissions reductions over a given time horizon and, therefore, is consistent with a long-term sustainability goal, i.e., the stabilization of atmospheric CO_2 concentration. In contrast with the imposition of stringent short-term reduction caps attendant to the “where” flexibility, allowing “when” flexibility could bring, among others, benefits related to avoiding the premature phase-out of existing capital-intensive energy technologies and related infrastructure, thereby reducing the cost of CO_2 abatement.

Related to these two aspects of policy flexibility is the role of technological change. Technology is recognized to play a key role in GHG mitigation strategies. Clearly, the technologies that would intervene in a mitigation strategy depend on, among other factors, the degree to which the “when” and “where” policy flexibilities are implemented, as well as the rates of technological progress through ETL. By stimulating learning processes associated with low-carbon, more-efficient, and clean energy technologies significant benefits can accrue. Hence, the role of ETL is addressed in this chapter.

In summary, this analysis quantitatively elaborates on the following research questions using the GMM model:

- What are the economic and technology-mix implications of the “where” flexibility mechanism involving full trading of CO_2 emission permits at a world level?
- How will the effects of full emissions trading be affected by the introduction of “when” flexibility?
- How will the results of the previous two inquiries be changed if countries/regions were to support policies for technology diffusion and learning of low-carbon technologies?

This chapter is organized as follows: Section 5.1 presents the scenarios examined and the CO_2 emission reduction targets imposed on the global energy system. Section 5.2 discusses the GMM results at the global level, and stresses the role of the “where” and the “when” flexibility policy options, as well as the implications of policies designed to stimulate technology learning in a CO_2 mitigation strategy. Finally, Section 5.3 concludes by summarizing the core findings and policy recommendations.

5.1. *Scenarios*

For the CO_2-cap&trade scenario, a carbon-constrained world is assumed, wherein smooth global carbon-emission reduction commitments towards an emission target of 10 GtC/yr by the year 2050 are specified (see Section 5.1.1 for further details), as is given in Table 11. Each GMM region applies its specific CO_2 reduction entitlement, contributes to carbon-reduction efforts, and simultaneously trades carbon emission permits.

Year	2010*		2020		2030		2040		2050	
Region	*Emission target (GtC/yr)*	*Reduction over Baseline (%)*	*Emission target (GtC/yr)*	*Reduction over Baseline (%)*	*Emission target (GtC/yr)*	*Reduction over Baseline (%)*	*Emission target (GtC/yr)*	*Reduction over Baseline (%)*	*Emission target (GtC/yr)*	*Reduction over Baseline (%)*
OOECD	1.3	-17.3	1.2	-21.0	1.2	-22.9	1.2	-24.5	1.1	-29.1
NAME	n.a.	0.0	1.9	-16.9	1.9	-26.4	1.8	-24.9	1.7	-28.2
EEFSU	1.3	25.5	1.2	-3.7	1.2	-27.2	1.2	-47.3	1.2	-61.5
ASIA	n.a.	0.0	3.1	-10.5	3.8	-19.5	4.3	-29.9	4.1	-40.0
LAFM	n.a.	0.0	1.1	-10.5	1.3	-19.5	1.5	-29.9	1.7	-40.0
WORLD	n.a.	-0.2	8.6	-12.8	9.4	-22.4	10.0	-31.3	9.9	-41.3

Table 11. *Carbon-emission reduction targets in the CO_2-cap&trade scenario.* In 2010, only OOECD and EEFSU regions are committed to reduce CO_2 emissions.*

Implementation of the carbon constraint in GMM assumes the amount of regional CO_2 emissions (minus CO_2-capture and sequestration, *Seq*) should be below a fraction *fr* of the reference (*REF*) emissions. The CO_2 balance is made considering the primary-energy use of fossil fuels (i.e., $fossil_{r,ff,t}$) and their specific emission coefficients (i.e., SE_{ff}), while sequestration options applied to a technology (*j*) for electricity generation (*ELE*) are associated with negative emission coefficients per unit of kWh produced.

$$\sum_{r,ff} fossil_{r,ff,t}^{CO_2cap} \cdot SE_{ff} - \sum_{j \in Seq} ELE_j \cdot SE_j \leq (1 - fr_{r,t}) \cdot \sum_{r,ff} fossil_{r,ff,t}^{REF} \cdot SE_{ff} \quad (9)$$

The parameter $fr_{r,t}$ is the fractional reduction of carbon emissions below the reference case by region (*r*) and time (*t*) such that a reduction target (*CO_2 cap*) is fulfilled. This regional fraction takes into consideration the aspiration of third world countries for economic development. Since the constraint is applied at the global level, trade of emission permits is allowed.

To address the research questions posed above, three main and four supplementary global scenarios are investigated, each of which consideres a selected type of flexibility (e.g., “where” or “when”) and different trade and learning modalities. Table 12 defines these scenarios and the naming conventions used.

Scenario	Specification	Flexibility
Main scenarios		
Baseline	Baseline case, a tax of 10\$/tCO_2 applied in OOECD in 2010-2050, with ETL	
CO_2-cap&trade	Regionalised CO_2 reduction target, Partial equilibrium, Trade of emissions permits, ETL	"where"
CUM-CO_2-cap&trade	Cumulative CO_2 reduction target, Partial equilibrium, Trade of emissions permits, ETL	"where + when"
Supplementary scenarios		
CO_2-cap&no-trade	Regionalised CO_2 reduction target, Partial equilibrium, No-Trade of emissions permits, ETL	
CO_2-cap&trade/no-ETL	Regionalised CO_2 reduction target, Partial equilibrium, Trade of emissions permits, No-ETL	"where"
CUM-CO_2-cap&no-trade	Cumulative CO_2 reduction target, Partial equilibrium, No-Trade of emissions permits, ETL	
CUM-CO_2-cap&trade/no-ETL	Cumulative CO_2 reduction target, Partial equilibrium, Trade of emissions permits, No-ETL	"where + when"

Table 12. *Naming and description of the CO_2-abatement policy scenarios.*

In the analyses presented below, the most important scenarios are the Baseline, CO_2-cap&trade and CUM-CO_2-cap&trade scenarios. The Baseline scenario corresponds to the reference development with globally unconstrained carbon emissions but with endogenous technological learning (ETL), as is described in Chapter 4. The CO_2-cap&trade and CUM-CO_2-cap&trade scenarios represent two alternative specifications of the same carbon constraint using different kind of policy flexibility in CO_2-abatement, as defined in following Section 5.1.1. A group of four supplementary scenarios has been developed to contrast the main scenarios with the consequences of different policy actions, i.e., exclusion of emissions trade or exclusion of ETL. The generic carbon tax applied for OOECD in the Baseline is not adopted in the carbon-constrained scenarios. Although not exhaustive, the scenario set depicted in Table 12 covers a broad range of possibilities.

5.1.1. CO_2 emissions targets

The carbon emissions targets of the CO_2-cap&trade scenario are set according to the CO_2 constraints for each of the five world regions, as prescribed in Blanchard et al. (2001) for the so-called "Soft-landing" scenario. In this scenario, CO_2 concentrations are stabilized in the long term at about 550 ppmv of atmospheric CO_2, and all countries contribute to emission reduction. The 550-ppmv concentration target is frequently used as a precautionary, but attainable, level and represents the middle value of stabilisation level identified by Wigley et al. (1996). The global emission trajectory of the CO_2-cap&trade scenario is similar to those presented in literature (Riahi and Roehrl, 2000; Wigley et al., 1996; IPCC, 2001a). The allocation of emission entitlements takes into consideration the aspirations of less-developed countries for economic growth and distributes total emissions such that a smooth trajectory to 10 GtC/yr will be obtained prior to 2050, with a decline subsequently (ACROPOLIS, 2003). The timing of imposed carbon-emission constraint follows the IPCC emission pathway, which implies the maximum energy-related CO_2 emissions of 10 GtC/yr by ~2030 (excluding about 2 GtC/yr from agriculture sector) (IPCC, 2001a).

For defining regional CO_2 reduction entitlements, certain rules apply. With regard to differences in energy and economic dynamics across the world regions (*r*), a differentiation is maintained in the CO_2-cap&trade scenario between industrialised countries and developing countries, as introduced by the Kyoto protocol. For the Annex B countries (*AB*), the emission reduction rate (*Krr*) is the same as established in the Kyoto protocol for the first commitment period 1990-2010. For example, if the reduction target for the EU in 2010 is 8 % below 1990, its carbon emissions (*CEM*) in 2030 should not exceed 0.92*0.92 times its emission levels in 1990:

$$CEM_{EU,2030} \leq CEM_{EU,1990} * (1 - Krr_{EU})(1 - Krr_{EU}) \text{, while } EU \in AB \tag{10}$$

This rule, however, does not apply in setting carbon constraints for developing countries. For the non-Annex B countries (*NAB*), stabilisation targets are based on 2010 emissions, the GDP per capita and projections of the population growth; for details see Blanchard et al. (2001). It is assumed that by around 2030 the increase in carbon emissions from developing regions must be at most equal to the reduction of the Annex B countries:

$$\Delta CEM_{NAB,t} = CEM_{NAB,t}^{REF} - CEM_{NAB,t} \leq fr_{AB,t} \tag{11}$$

To achieve a stabilisation of carbon concentrations, the global emissions and those of the non-Annex B countries should in the longer term stabilise and eventually decrease, according to:

$$\sum_r CEM_t = CEM_{AB,t} + CEM_{NAB,t} \text{, and } \sum_r CEM_{2050} < 10GtC \tag{12}$$

The regionalized CO_2 emissions rates under conditions imposed for the CO_2-cap&trade scenario are shown in Figure 13. These emission rates imply the adoption of domestic and international CO_2 reduction policies outlined in Table 2, and allow for the overall emissions stabilisation. Moderate annual growth rates in CO_2 emissions of 1% and 1.4% are allowed in ASIA and LAFM regions between the years 2020 and 2050 to account for expected economic and population growth in these regions. On the contrary, emissions in the industrialised regions are forced to decline from 2020 onward, with annual declination rate of –0.1% in EEFSU, -0.3% in OOECD, and –0.4% in NAME region. It is assumed that around 2010 the OOECD and EEFSU regions fulfil their emission-reduction obligations given by the Kyoto protocol (UNFCCC, 1999).

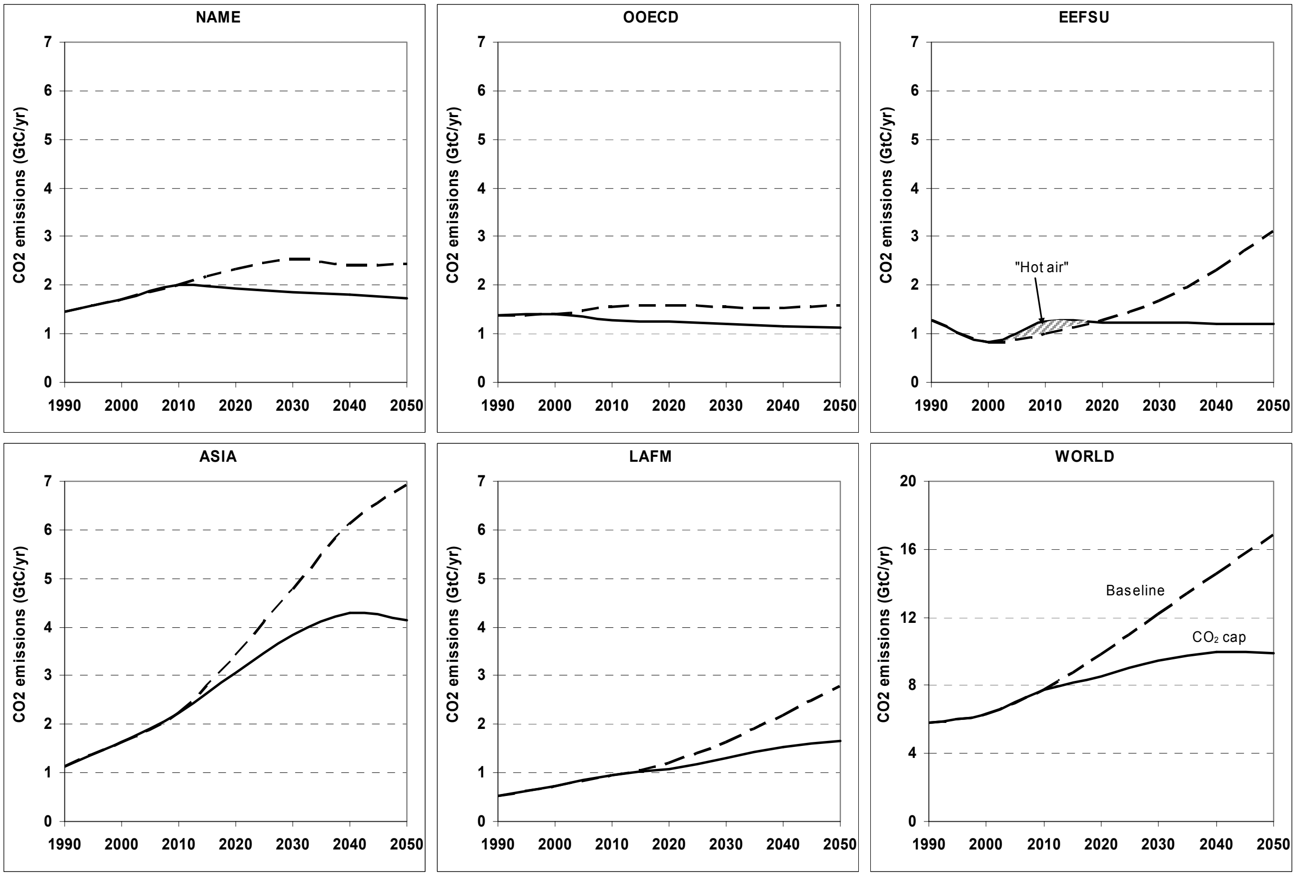

Figure 13. *Regional and global CO_2 emission rates under Baseline (dotted line) and under constraint applied for the CO_2-cap&trade scenario.*

The scenario presented in this analysis is one of many possible scenarios that integrate developing countries into the emission-reduction process aiming at the 550-ppmv stabilisation targets on the global level. An example of different emission reduction targets for the same atmospheric CO_2 concentration level can be found in Labriet et al. (2005), where, for example, the short-term ‘Kyoto-like’ carbon mitigation policies are exceeded by imposing higher global emissions reduction rates between 2010-2020.

Alternative approaches in setting CO_2 caps are examined herein by using a cumulative constraint in the CUM-CO_2-cap&trade. Instead of setting annually fixed emissions limits for each time period, a cumulative CO_2 constraint for the whole commitment period is specified to equal the integral of the regionalized annual bounds depicted in Figure 13 for the CO_2-

cap&trade scenario. Simultaneously, the trading of carbon permits between regions is allowed. Optimising under these conditions allows for the aforementioned "when" and "where" flexibility options in carbon mitigation policy to be examined and promises the maximum possible efficiency in meeting the specified carbon constraints. Based on the results of the cumulative constraint, it is possible to evaluate and compare the technological and economic implications and to verify how 'optimal' the carbon emissions targets are; see Section 5.2 for further details.

The CO_2-cap&trade scenario assumes late participation of USA in the CO_2 reduction policy (i.e., the US implements only domestic policies up to 2010 and joins the global emission permit trade in 2020). After 2010, all regions can trade carbon permits as long as they accept emission reduction obligations, and, therefore, CDM projects are not explicitly modelled. In the period around 2010, where the Kyoto protocol applies, only 50% of the Former Soviet Union and Eastern Europe's "hot air" availability (Sager, 2003a) can be traded with other Annex B countries, while the other half is assumed to be lost, since no banking of any kind is considered; see the following Section 5.1.2.

5.1.2. Hot air

The origin of so-called "hot air" in the countries of the Former Soviet Union and Eastern Europe (EEFSU) is the dramatic economic loss and the associated strong decrease in energy use in this region in the last decade of the 20th century. Consequently, a 30% drop in carbon emissions occured between the years 1990 and 2000 (IEA, 2002c). According to the emission-reduction objectives proposed by the Kyoto protocol, the CO_2 emissions of these regions should remain at the same level as in 1990. Therefore, the economies-in-transition within the EEFSU region (Annex B group members) could in principle sell the full amount of "hot air" permits to countries that face binding Kyoto constraints without undertaking any further reduction in their own current emissions.

Some studies (e.g., Eyckmans et al., 2001; Den Elzen and De Moor, 2001; Sager, 2003b) indicate, however, that EEFSU countries for the sake of their own profit-maximisation should instead impose certain restriction on their "hot air" availability for trade. To reflect this argument, EEFSU countries are allowed in the GMM model runs to trade only 50% of their "hot air" emissions in 2010. The expected amount of "hot air" available for trade in the first commitment period certainly depends on the economic growth in the EEFSU regions. Literature sources estimate this amount to be within the range of 0.15 to 0.5 GtC/yr in 2010

(Haurie and Viguier, 2003). Based on the estimated level of emissions in the baseline scenario, the amount of "hot air" adopted in GMM is 0.26 GtC/yr, as graphically illustrated in Figure 13.

5.1.3. Specification of emissions trade

Trade of CO_2-emission permits is specified in two main (CO_2-cap&trade and CUM-CO_2-cap&trade) and two supplementary (CO_2-cap&trade/no-ETL and CUM-CO_2-cap&trade/no-ETL) scenarios, according to the current climate policy as defined in the Kyoto protocol and the recent Marrakech agreement (Den Elzen and De Moor, 2001). "Hot air" can be traded only in the period around 2010, but at the same time an upper bound of 50% of the total "hot air" availability is imposed. Trade takes place in 2010 only between OOECD countries and the EEFSU region (both in the group of Annex B); the NAME region is excluded from trading during this time period. Afterwards, all world regions are allowed to trade carbon-emission permits. The resulting total amount of traded permits and the respective time development under the carbon-constrained scenarios are discussed in Section 5.2.2.3.

5.2. Scenario Results

This section describes the main findings from different scenarios relative to the Baseline case and the implications of flexibility and learning modalities for the CO_2 emission reduction policies studied. Results presented here emphasise the global developments of primary and final energy consumption, the structural changes in power generation, e.g., fuel mix, choice of technologies, and the overall system costs. Impacts of the CO_2 mitigation policies on the carbon emissions are reported in the form of regional trade of emissions permits and the respective marginal costs. Additionally, global indicators, e.g., energy and carbon intensity are used to describe the behaviour of the energy system under selected scenarios.

5.2.1. Structural changes

5.2.1.1. Electricity generation

The imposed carbon-emission reduction target decreases the overall power generation in 2050 by 5.2% for the CO_2-cap&trade scenario and by 3.7% for the CUM-CO_2-cap&trade scenario, relative to the Baseline, since the production cost of electricity and, therefore, the price of electricity increases. Figure 14 shows a similar evolution in the power-generation mix for both carbon-constrained cases. Imposition of the carbon constraint results in a strong reduction of coal use for power generation; a decrease by 48% for the CO_2-cap&trade scenario and by 44% for the cumulative constraint over the Baseline in the final year 2050 is reported. The only coal-based technology that undergoes significant increase in both scenarios compared to the Baseline scenario is the IGCC with carbon capturing; this technology supplies nearly 9% of total power generation in 2050.

The reduction in coal-based power production is less pronounced in the CUM-CO_2-cap&trade scenario between 2010-2030, however, the penetration of the systems with CO_2-capture is higher in the end of time horizon. Instead of coal, carbon-free renewable and nuclear electricity sources are chosen, and their combined share reaches 47% by 2050. Renewable electricity sources increase their contribution by 21% as compared to the Baseline scenario. Non-biomass renewable electricity-generation potential in 2050, as presented in Table 9, is exploited to the extent of around 35% in both scenarios. Generation systems based on NGCC become the dominant source of electricity by the end of the time horizon for the CO_2-cap&trade scenario and provides 26% of the total annual generation in 2050.

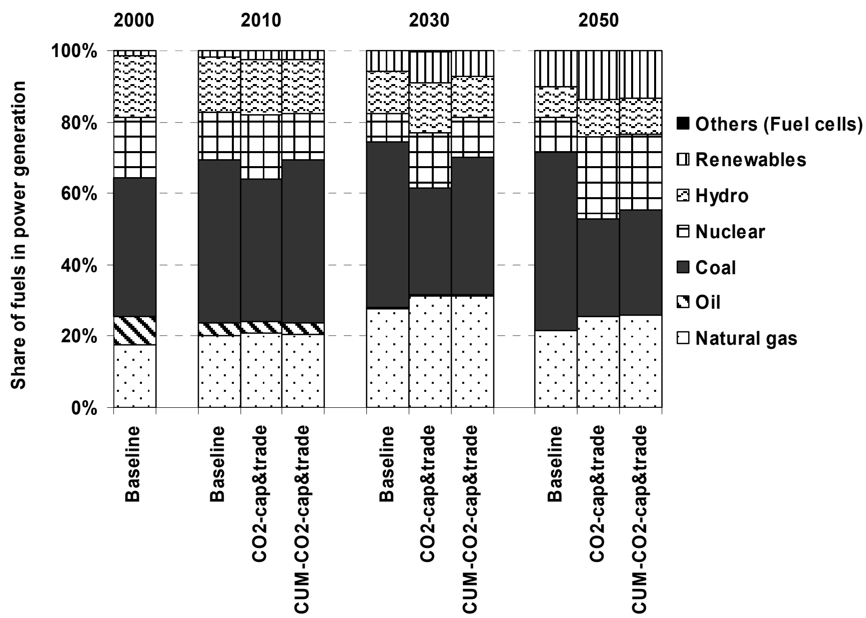

Figure 14. *Development in the electricity production by fuel type in the carbon-constrained scenarios (relative shares).*

Figure 15 compares electricity generation by technology in the year 2050 for the three main scenarios (Baseline, CO_2-cap&trade and CUM-CO_2-cap&trade) and leads to a deeper presentation of the technological spectrum under different policy settings. Under the carbon constraint, both conventional and advanced-coal generation (including PFBC and IGCC) are significantly reduced as compared to the Baseline development. Advanced coal technologies (e.g., PFBC, IGCC) with CO_2-capture, however, penetrate the market at a substantial level, and play an important role in achieving the CO_2 emissions-reduction target. The coal-based generation is displaced in favour of natural gas (NGCC), and above all, by nuclear power plants. Finally, a significant increase in production from hydropower, wind, biomass and geothermal sources is reported in the year 2050 for both carbon-constrained cases.

The main difference in generation mixes in 2050 between the two policy-scenarios is a higher total power production from nuclear and renewable-energy systems in the CO_2-cap&trade case, while the CO_2-capture and NGCC plants penetrate at a higher levels in the CUM-CO_2-cap&trade scenario.

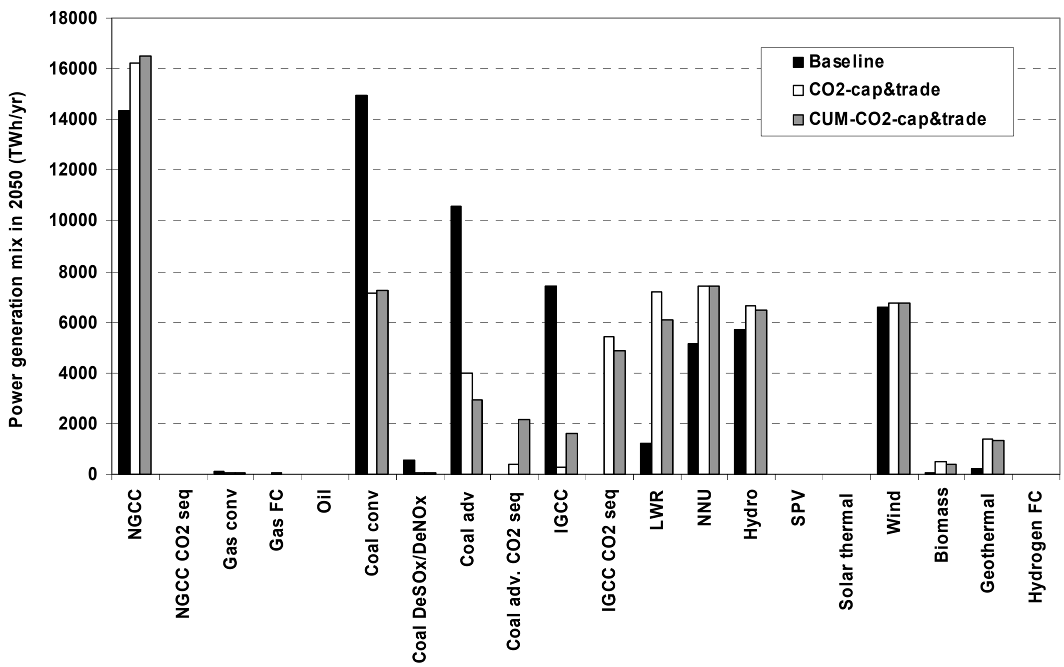

Figure 15. *Contribution of technologies to the global electricity generation mix in 2050 in the carbon-constrained scenarios. For nomenclature, see Table 8.*

Figure 16 elucidates which technologies contribute to global power generation in the carbon-constrained CO_2-cap&trade scenario, for the years 2030 to 2050, with and without ETL. The outcomes of technology penetration depend on a number of key factors, such as the exogenous bounds applied, market penetration rates and the learning-by-doing elasticities. These results illustrate that the differences in the power-generation mix can be significant, and, as expected, the structural changes caused by incorporation of ETL are more significant in 2050 as compared to 2030.

In 2030, the most pronounced shift is the more rapid substitution of coal-based power generation with the NGCC systems and a larger penetration of wind turbines. In the CO_2-cap&trade scenario with ETL, the additional demand for less carbon-emitting electricity sources in 2050 is met predominately by a higher penetration of 'learning' technologies, such as NGCC, and systems incorporating CO_2 sequestration, as compared to the scenario without ETL. In 2050, differences in the power generation from advanced nuclear plants and wind turbines are not significant, since the penetration of these technologies approaches limits defined by the maximal (exogenous) annual growth rates. On the other hand, the IGCC systems without carbon removal, hydropower, and conventional nuclear plants penetrate at higher levels when ETL is not included. Total electricity production in 2050 is higher by 2% in the CO_2-cap&trade scenario compared to the case without ETL, since ETL reduces the electricity generation costs, and consumption thereby increases.

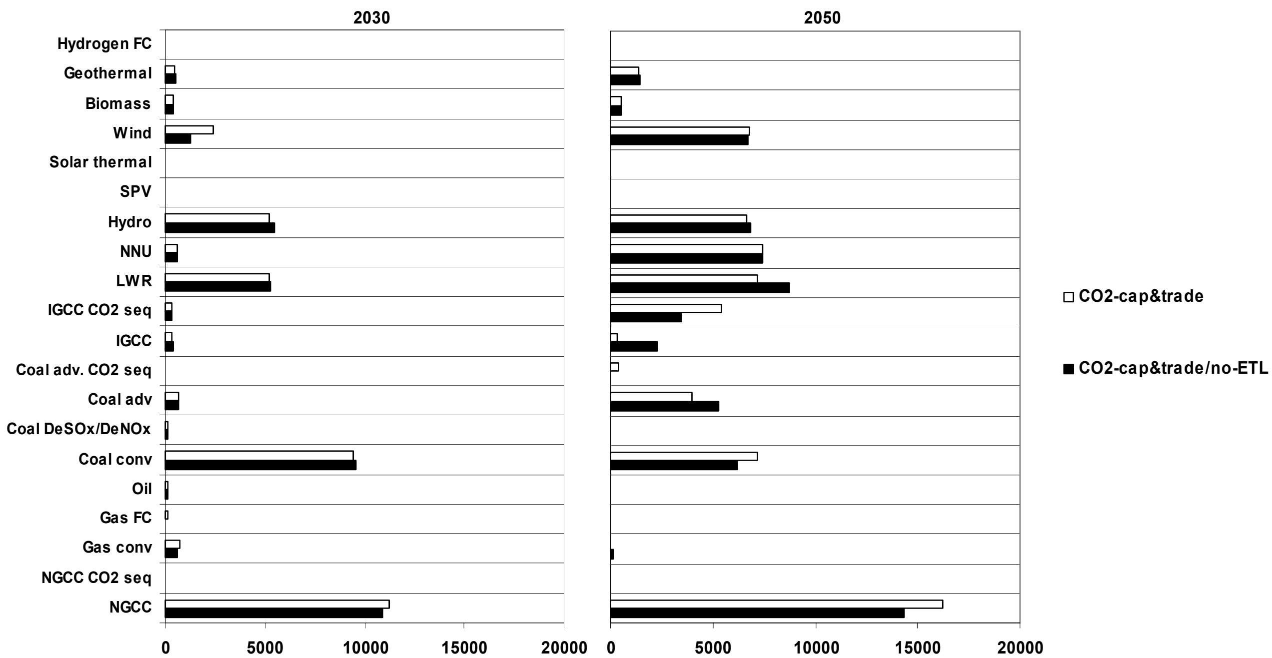

Figure 16. *Comparison of electricity generation (TWh/yr) in 2030 and 2050 in the CO_2-cap&trade scenario with and without ETL*

5.2.1.2. Primary energy consumption

The global primary-energy consumption decreases for the carbon-constrained scenarios. In the year 2050, a 2% (i.e., in the CO_2-cap&trade scenario) and 1% (i.e., in CUM-CO_2-cap&trade scenario) reductions relative to the Baseline are observed.

In both scenarios, a significant increase in the contribution of non-fossil sources, i.e. nuclear energy and renewables, is reported over the timeframe 2000-2050, as indicated by Figure 17.

The contribution of nuclear energy doubles, and renewables increase the market share by 25% by 2050 over the Baseline. Although in relative terms nuclear energy shows maximum gains, in absolute terms renewable-electricity sources (including hydropower), renewable heat, and nuclear energy have similar contributions to primary-energy production. By the end of the time horizon consumption of coal is reduced by about 50% when compared to the reference case. A large fraction of coal in 2050 is used for combustion in advanced power plants equipped with CO_2-capture. Natural-gas consumption slightly increases in 2050 because of a higher use of natural gas in the electricity sector. Gradual reduction in oil use occurs over the whole time horizon.

The difference in the primary-energy consumption for the two carbon-constrained scenarios in 2050 is marginal; however, the changes over the Baseline scenario between 2020-2040 are smoother and gradual in the cumulative formulation of the carbon cap&trade policy. The policy implication of this outcome is that an optimal timing under the "when" flexibility in climate-policies might postpone the costly structural shifts in the energy system toward later decades while achieving the same CO_2-stabilization target.

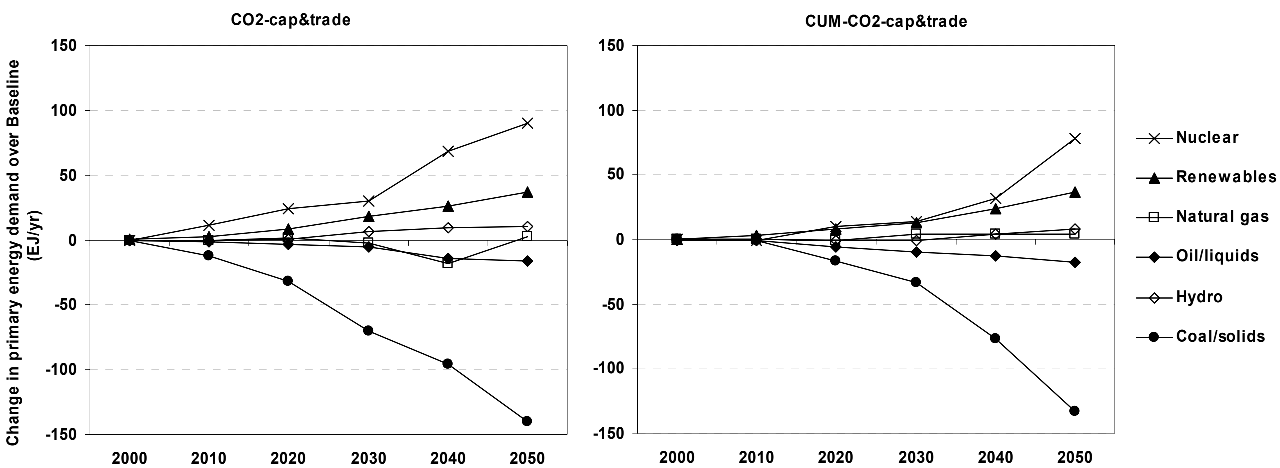

Figure 17. *Change in global primary-energy use for the CO_2-mitigation policy scenarios compared to the Baseline.*

5.2.1.3. Final energy demand

Imposition of the carbon-abatement policies, as specified in this exercise, implies important changes on the demand side of the reference energy system. Since the carbon constraint causes an increase in the marginal cost of energy, the global final-energy demand is reduced relative to the Baseline. This reduction is slightly larger in the CO_2-cap&trade scenario as compared to the cumulative case, and reaches the level about 5% in 2050 for both carbon-constrained cases. Figure 18 illustrates that the most significant change observed in the final-energy markets is the reduced relative importance of fossil fuels, i.e., coal, oil products, and partly natural gas, also.

Demand for electricity is reduced as well relative to the reference case. At the same time, networks of district heating systems and the other energy carriers, i.e., biomass, solar-thermal energy, hydrogen and alcohol-fuels increase their market shares under the carbon-constrained scenarios. Figure 18 also shows that the level of demand reduction for electricity is lower in the CUM-CO_2-cap&trade scenario. This is explained by the lower electricity costs in the case of combining "where" and "when" flexibility in the carbon abatement efforts. A reduction in final-energy use of natural gas between 2030-2050 is due to increased gas consumption for the power generation dominated by NGCC systems.

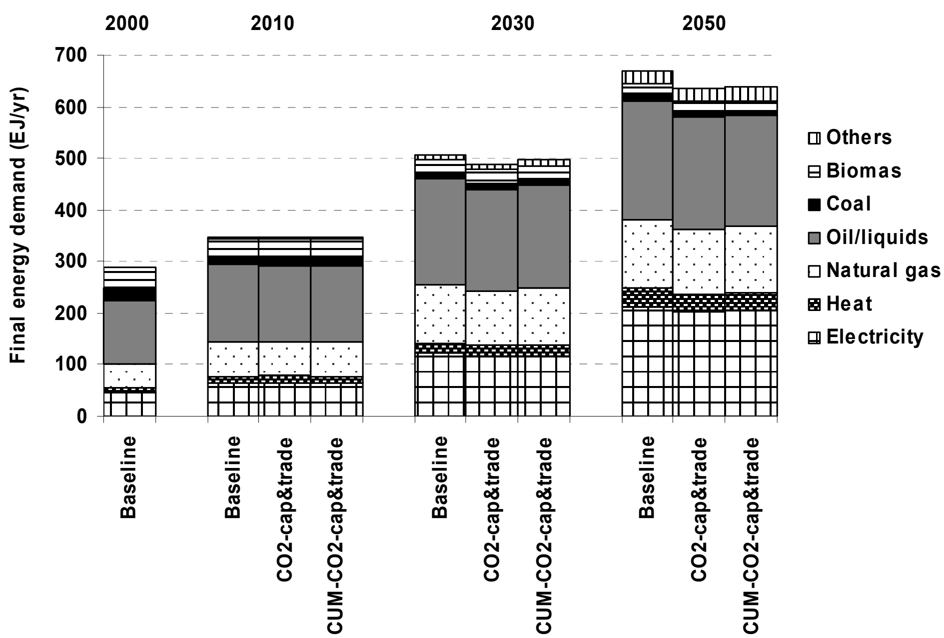

Figure 18. *Time evolution of final energy demand in the Baseline and in carbon-constrained scenarios.*

5.2.2. Environmental impacts

5.2.2.1. Global CO_2 emissions

Energy-related global carbon-emission rates in the Baseline scenario increase continuously throughout the time horizon modelled, giving an annual rate of 1.97 %/yr and reaching a level of 16.8 GtC/yr by the year 2050. Under the CO_2-cap&trade constraint active, CO_2 emissions continue to grow by around 2030, while a stabilised emission trajectory begins after 2030 to reach the level below 10 GtC/yr by 2050. Global carbon emissions decrease over the Baseline scenario by 41% in 2050 and represent an absolute reduction of 6.9 GtC/yr. The strongest carbon-emission decrease for the CO_2-cap&trade scenario occurs after the year 2020, when all regions have an obligation to reduce their CO_2 emissions.

The cumulative carbon-emission reduction over the reference development for the periods 2010 to 2050 is 26% under both CO_2-cap&trade and CUM-CO_2-cap&trade scenarios. The carbon emission trajectories, as shown in Figure 19, however, indicate minor differences between the two respective scenarios. Regional emission bounds for the CO_2-cap&trade scenario force smooth stabilisation after 2030. On the other hand, the CUM-CO_2-cap&trade scenario with flexible timing of imposing the CO_2 reduction target projects a stronger reduction in the period of 2050, but more emissions are allowed in earlier years.

As discussed earlier in Section 5.1.1, the goal of carbon constraint defined in this study is the long-run stabilisation of atmospheric concentrations of CO_2 to ~550 ppmv. This concentration target defines a cumulative amount of carbon emissions that should not be exceeded within a given time framework. A number of carbon-emission pathways, therefore, can be selected to meet the target, while these pathways differ in allocation of a global carbon budget over time (IPCC, 2001a). The timing in allocation of the carbon budget, which is directly addressed by the "when" flexibility modality in the CO_2-mitigation policies, might have a considerable cost implications, as is elaborated in Section 5.2.4.

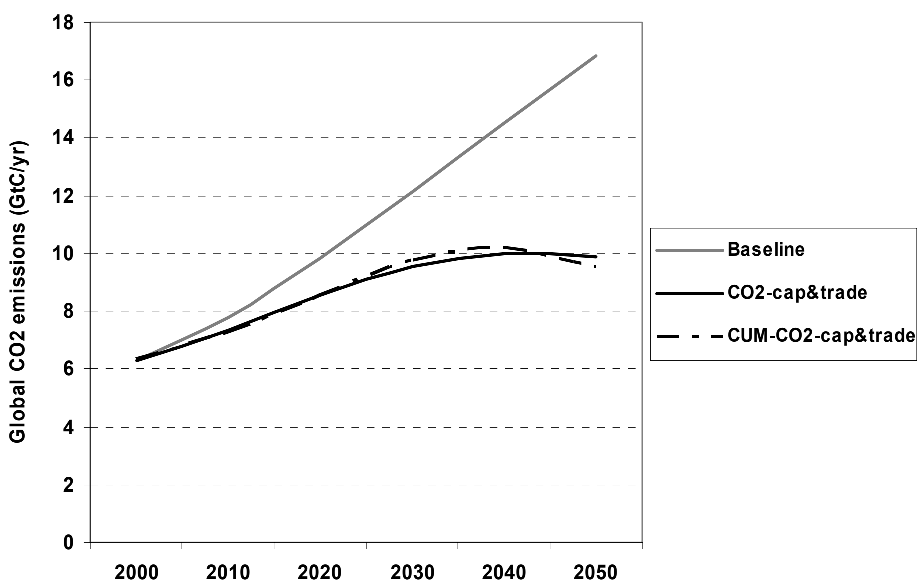

Figure 19. *Development of total global CO_2 emissions under the Baseline and carbon-constrained scenarios.*

5.2.2.2. Break-down of CO_2 reduction components

The decarbonisation effect of flexible CO_2-mitigation policies can be illustrated by allocating carbon abatement to the different CO_2-reduction components, as shown in Figure 20. Five carbon-reducing components were considered: a) inter-fossil fuel switching (i.e., from coal to natural gas); b) reduction of fossil fuel fraction resulting from increases in nuclear energy use; c) reduction of fossil-fuel fraction in favour of renewables; d) carbon capture and sequestration; and finally, e) the reduction of elastic end-use demands as a result of the policy-invoked price changes (Kypreos, 1990). It should be noted that most of energy-conservation measures are included in the exogenous reduction of the energy intensity underlying the Baseline scenario.

Over the entire time horizon, the inter-fossil-fuel switching plays a dominant role in carbon mitigation contributing by 61% and 68% to CO_2 reduction in 2010 and 2050. Carbon-free primary-energy sources also play an important role worldwide in the CO_2 emissions abatement for the policy scenarios, wherein contribution from nuclear energy declines from 35% to less than 15% in 2050. Renewables contribute 2-8% to the total reduction and the contribution in relative terms peaks around 2030. Reduction in end-use demand contributes to carbon mitigation by 6% in 2030, and declines in 2050.

Carbon capture and sequestration from fossil fuel combustion begins to play a significant role in the second part of the time horizon investigated. The share of carbon removal in the overall CO_2 reduction in 2050 corresponds to 13% in the CO_2-cap&trade scenario and to 18% in the CUM-CO_2-cap&trade scenario. The cumulative amount of carbon removal and sequestred in the CUM-CO_2-cap&trade scenario is nearly 16 GtC during the period 2010-2050. Although the total potential for carbon sequestration is not bounded directly in GMM, the cumulative amount of CO_2 captured and stored represents only about 6% of the global cumulative storage-potentials in depleted oil and gas fields estimated by IEA (2004b).

Considerable variances in total contribution of CO_2 reduction components, in particular the carbon sequestration, can be identified in other studies, e.g., in Labriet et al. (2005). These variances are determined by differences in baselines, emission reduction levels, assumptions on cost and availability of new technologies, resources availability, and price elasticises.

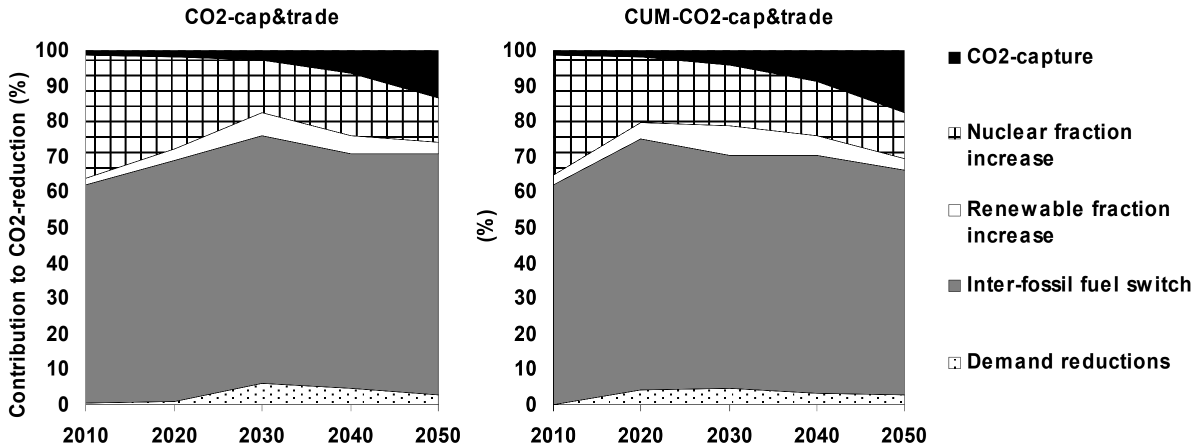

Figure 20. *Break-down of CO_2 reduction components under carbon-constrained scenarios.*

5.2.2.3. Inter-regional trading of CO_2 emission permits

The analysis of the inter-regional trading with CO_2 emissions credits is important for the assessment of economic and policy implications of CO_2 mitigation strategies. Assumptions related to specification of the "cap&trade" regime for the policy scenarios under examination are described in Section 5.1.

Figure 21 illustrates the development of carbon-emission permits trade within the five GMM regions under both CO_2-cap&trade and CUM-CO_2-cap&trade scenario conditions. In the former case, the amount of carbon permits globally traded among regions increase from 0.63 GtC/yr in 2020 to 1.07 GtC/yr in 2050. Despite the "hot air" restriction imposed in the first phase (see Section 5.1.2), the dominant suppliers of carbon credits are the EEFSU region (cumulative carbon permits supply of 26.4 GtC) and ASIA (over 5 GtC). The main buyer of carbon credits is the OOECD region, with resulting cumulative purchase of 14.5 GtC, and followed by the NAME region (10.2 GtC). Towards the end of the time horizon, a switch from a selling to a buying position is projected for the developing regions of ASIA and LAFM. This shift can be explained by the strong growth of energy demand based on fossil fuels in the 2030-2050 periods, and by the allocation of CO_2 emission reduction quotas.

The introduction of a cumulative constraint for the CUM-CO_2-cap&trade scenario combines the "where" and "when" flexibility in the CO_2-abatement policies. The "when"-flexibility allows for a time-efficient adoption of the carbon reduction targets. Instead of imposing emission limits for each time period, cumulative CO_2 endowments are established for the entire commitment period for each region, and the trade of CO_2 permits is allowed among the regions, as under the CO_2-cap&trade scenario. As is shown in Figure 21, the NAME and

OOECD regions remain major buyers of the CO_2 permits also under the cumulative constraint, whereas EEFSU region becomes a sole permits supplier. The results reveal, however, that global trade occurs mainly in the periods 2030-2040, which suggests that the regional emission quotas of the CO_2-cap&trade scenario coincide well with the allocation of emission reduction by region and time under the cumulative constraint.

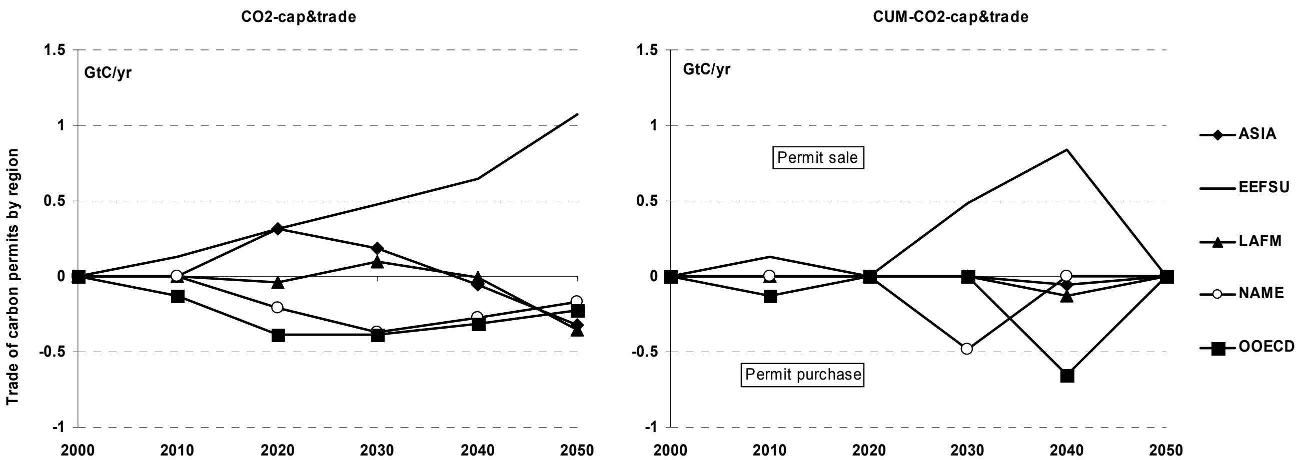

Figure 21. *Time dependence of inter-regional trading with CO_2 emissions permits.*

5.2.3. Global indicators

Following the Kaya identity for carbon emissions, as is discussed in Chapter 4, a set of additional indicators has been used to analyse behaviour of the RES for the carbon-constrained scenarios. First, the primary-energy intensity (i.e., the primary-energy consumption per unit of GDP) is plotted versus time in Figure 22a. The three main scenarios show similarly stronger reductions by the year 2010, followed by a period of slower reduction; an annual declination rate of -1%/yr for primary energy intensity is observed for the second phase. The total reduction in energy intensity over the Baseline scenario is most pronounced around 2030 in the CO_2-cap&trade scenario, since the energy demand reductions and technology shifts are largest in this time period.

In Figure 22b, the carbon intensity for the global RES is shown and describes the amount of CO_2 emitted per GJ of primary energy consumption for the Baseline and the carbon-constrained scenarios. The global carbon intensity for the Baseline scenario increases slightly until the year 2030, and subsequently stabilises as less carbon-emitting sources gain market shares. On the other hand, the decarbonisation effects under the CO_2-cap&trade and CUM-CO_2-cap&trade scenarios commence from the beginning of the time horizon investigated. The carbon intensity follows similar trends in both CO_2-constrained cases, with the annual declination rate of about -1.2%/yr.

The decarbonisation trend of the energy sector is further portrayed when emission results are expressed per unit of economic activity, i.e., the global amount of CO_2 emissions per unit of GDP, as a function of time. Figure 22c indicates a strong decrease in this indicator under both main carbon-reduction scenarios. While the decrease in the Baseline scenario in 2050 relative to the year 2000 is 30%, in the carbon-constrained cases reductions are in the range of 59% to 61%. The annual rates of decrease between 2000-2050 for the Baseline and CO_2-cap&trade cases are of -0.7%/yr, and -2%/yr, respectively.

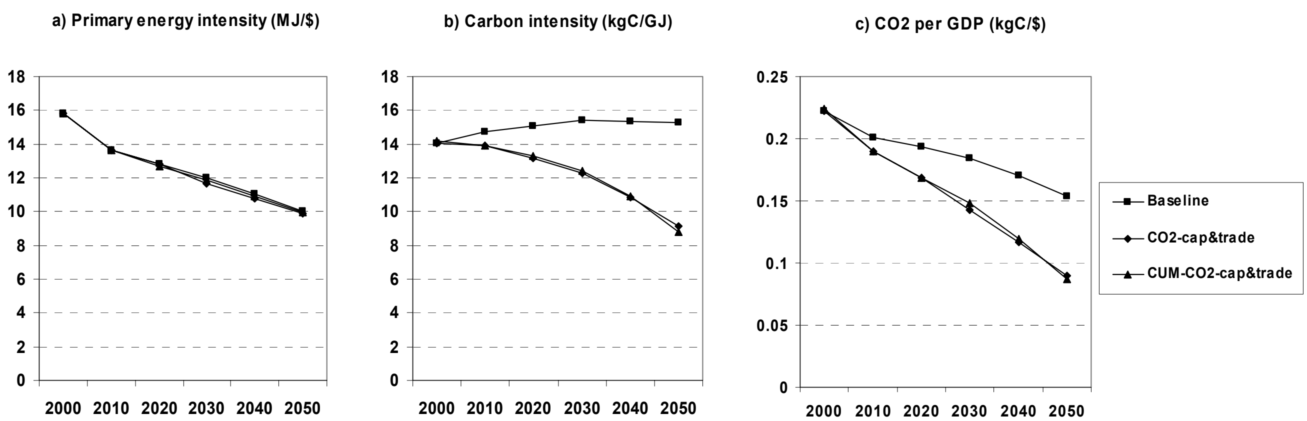

Figure 22. *Development in selected global indicators under Baseline and carbon-constrained scenarios.*

Regional comparisons of CO_2 emissions per capita under the CO_2-cap&trade scenario in Figure 23 show the highest value of this indicator for the NAME region all over the studied period despite considerable emission-cuts in the last periods resulting from active carbon reduction policies. The rates of this indicator for the OOECD region steadily decrease after 2000, but at generally lower values. On the other hand, the EEFSU region experiences an increase up to the period 2020 and subsequently declines with a rate -0.08%/yr over the remainder of the time horizon because of the projected changes in the RES and the trade modalities. The CO_2-per-capita ratio gradually increases in the developing world between 2000-2040, however, the levels represent only less than 25% of those reported for the industrialized countries. On the global level, this indicator decreases by more than 40% in relation to the Baseline scenario.

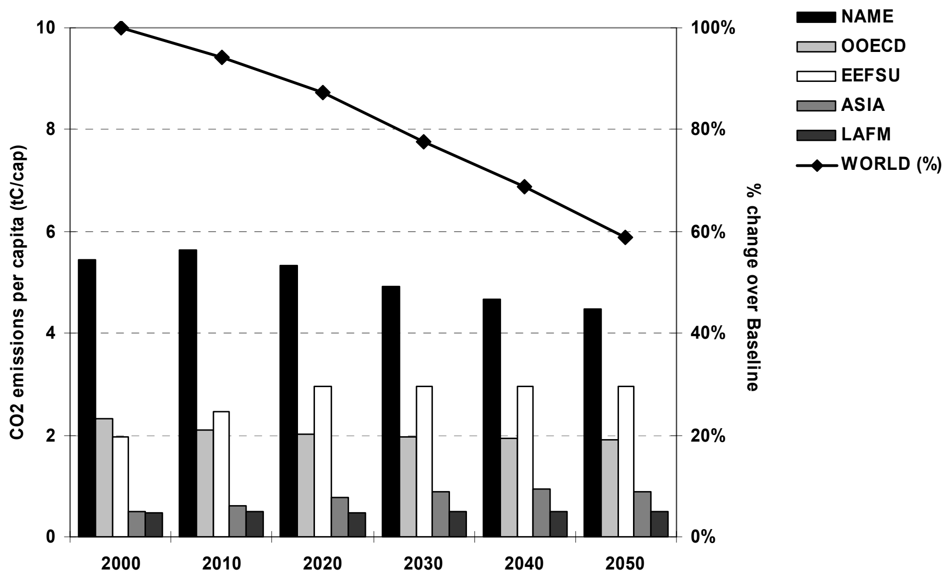

Figure 23. *Development of regional CO_2 emissions per Capita under the CO_2-cap&trade scenario.*

Figure 24 illustrates, how the carbon-reduction target specified for the CO_2-constrained scenarios is achieved under different policy options by plotting Baseline-normalized carbon intensity versus energy intensity based on primary energy, all expressed as a function of time. All carbon-reduction scenarios tend to achieve the target by reduction in carbon intensity. Projections of how the reference energy system reacts to meet respective policy goals, however, vary somewhat across scenarios.

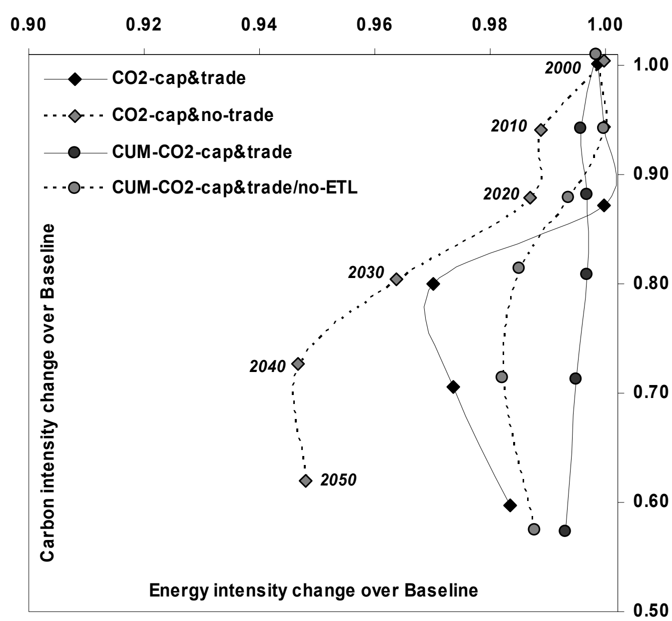

Figure 24. *Projection of changes in energy and carbon intensity relative to the Baseline for selected carbon-constrained scenarios. (Index: Baseline = 1)*

The strong decarbonisation effect of the CO_2-cap&trade scenario results in a decrease in carbon intensity by 40% in 2050 relative to the Baseline scenario; this reduction is slightly higher in the end of time horizon under the cumulative carbon constraint. In the CO_2-cap&trade scenario the reduction in energy intensity grows between 2020-2030 and subsequently becomes lower towards the end of time horizon. The decrease in energy intensity is the most pronounced in the CO_2-cap&no-trade scenario, where the absence of trade of carbon-emission permits leads to the strongest demand reduction. Similarly, a higher reduction in energy intensity is reported between 2020 and 2050 in the CUM-CO_2-cap&trade/no-ETL scenario, as compared to the case with the ETL option active.

5.2.4. Cost impacts

5.2.4.1. Carbon permit price

Marginal carbon-abatement costs (equal to carbon-emission permit prices) are presented for five selected scenarios in Figure 25. Carbon permit prices vary across scenarios and over time. Differences are determined by the level of the severity of carbon constraint relative to the Baseline scenario, the dynamics of technological change (ETL), and the trade specifications.

In all scenarios, the price of carbon permits increases over the time horizon, with the exception of the period around 2020. The reduction in marginal cost in this period is explained by the increased supply of carbon permits originated from Non-Annex-B countries joining the carbon-mitigation regime from 2020 onward. In 2050, the carbon-permit price reaches 145 $/tC for the CO_2-cap&trade scenario. Under the cumulative definition of the carbon constraint, the carbon permit price decreases significantly in the second half of the horizon as a consequence of the “when” flexibility in the mitigation policies. In this case the carbon price reaches 116$/tC, which represents a 20% reduction in 2050 over the CO_2-cap&trade scenario.

When the ETL option is not active, as under the scenarios CO_2-cap&trade/no-ETL and CUM-CO_2-cap&trade/no-ETL, the increase in the price of permits in 2050, induced by the absence of policies supporting the technology learning, is 6% in the former and 3.5% in the later case. Figure 25 also shows marginal costs of carbon reduction in the CUM-CO_2-cap&no-trade scenario, where inter-regional trade of carbon permits is not allowed. The range of marginal cost in 2050 varies from 41 $/tC for the EEFSU region to 364 $/tC for the NAME region and reflects regional differences in emission reduction potential and the severity of emission reduction targets imposed.

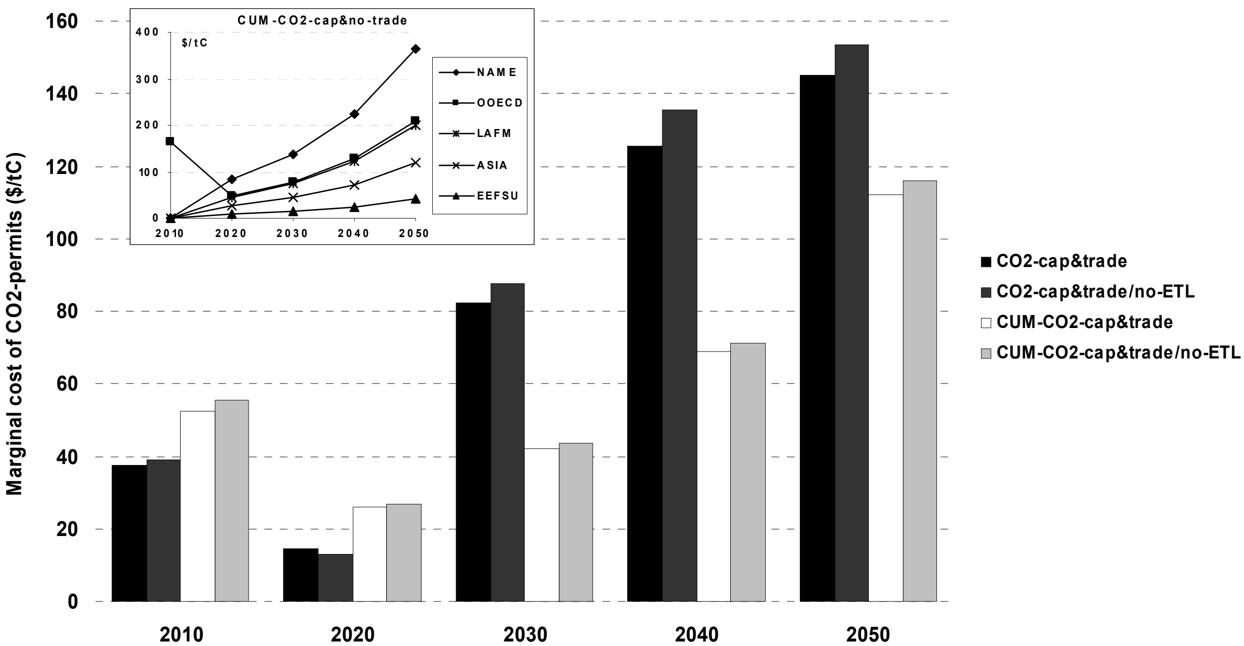

Figure 25. *Marginal cost of carbon emission permits reported for selected CO_2-mitgation scenarios versus time.* <u>*Inset*</u>*: Marginal cost of carbon reduction by regions in the scenario with absence of inter-regional trade of carbon permits.*

5.2.4.2. Total system cost

Different policy modalities in achieving the carbon-emission reduction target, as specified for this modelling exercise, might result in considerable cost-impacts for the energy system. Figure 26 documents the relative changes in the discounted cumulative energy system cost together with the welfare loss (sum of consumers and producers surpluses) for all the CO_2-mitigation scenarios analysed herein, as compared to the Baseline scenario.

Relative increases in the discounted energy system cost in the case of a cumulative carbon constraint enforced in conjunction with active ETL and trade options is reduced by 15%, as compared to the CO_2-cap&trade scenario with fixed annual reduction bounds. This result indicates the benefits of a less-stringent timing of achieving the carbon-mitigation burden, i.e., "when" flexibility. Contrarily, if the reduction entitlements are applied without possibility to trade carbon permits, the total system cost is increased by 47% relative to policy allowing for carbon-permit trade among world regions.

Furthermore, the presented results suggest that policies helping the advanced technologies to follow the respective learning curves (ETL) can moderate cost penalty associated with implementation of climate-response measures by 40%. Still, although models based on perfect-foresight algorithms, such as GMM, indicate that carbon-free systems will become competitive in the long term, this expectation is probably not realistic for the conditions under which "real-world" markets operate. Solar Photovoltaic or H_2-driven fuel-cell systems at the present stage of development are expensive compared to conventional fossil-fuel systems. Policies that favour introduction of these advanced technologies are necessary for their establishment in the markets to an extent where technical progress along the respective learning curves and the attendant reduction in specific (unit) costs can occur (IEA, 2003).

Changes in the energy system costs and marginal costs of carbon reduction indicated in this section are within the cost range reported by comparable studies (e.g., Labriet, et al., 2005). Similar findings concerning the effect of LBD are also reported in the literature (Manne and Richels, 2002). Finally, to give a sense of magnitudes involved, the total discounted system cost is about 70 trillion $\$_{2000}$ (10^{12} \$) for the Baseline scenario.

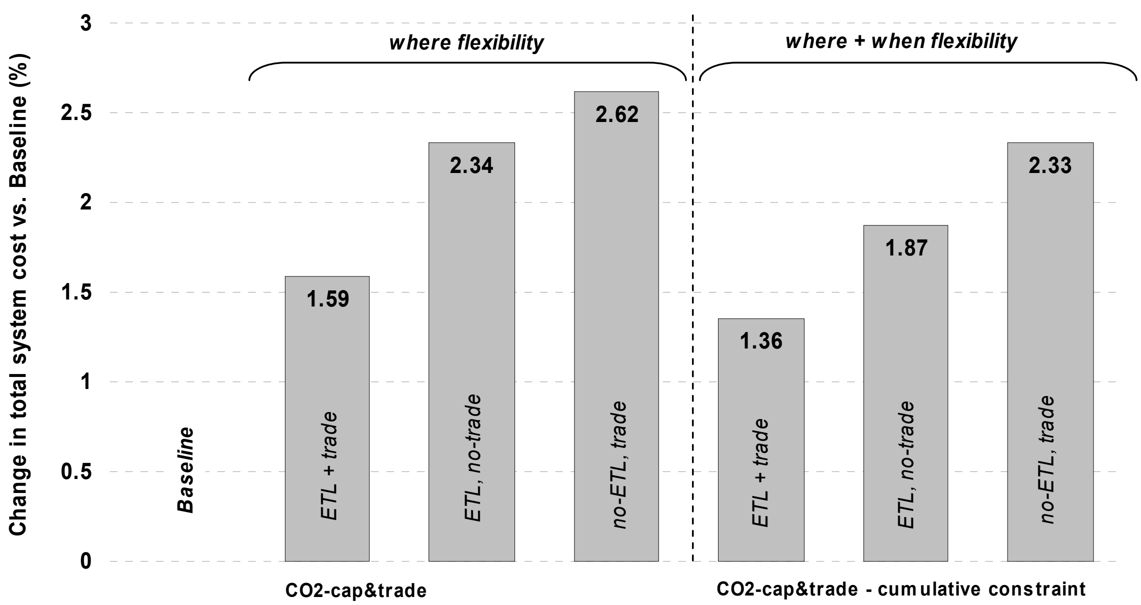

Figure 26. *Relative change in the cumulative discounted energy system cost over the Baseline for different modalities of the CO_2-cap&trade scenario.*

5.3. Summary and concluding remarks

This chapter investigates the implications of different flexibility modalities of an international CO_2 cap&trade regime and quantifies the corresponding structural changes and technology dynamics in the global energy system using the five-region Global MARKAL Model.

The scenario imposing smooth, regionalised carbon-emission caps over the time horizon has been used to illustrate the important role of spatial, temporal and technology-related flexibility in CO_2 mitigation within the global energy system. Generally, “flexibility” reflects the ability of the global energy system to effect a transition towards a low-carbon, more sustainable regime in the long term, while accommodating large technological, social and economic uncertainties. The long-lived infrastructures and technological regimes that typify the global energy system lead to large inertia. Therefore, policies are necessary that facilitate such transition while minimizing associated costs. In this chapter, the analysis is provided on how the carbon-emission reduction targets, aiming at the long-term stabilization of the atmospheric CO_2 concentration at approximately 550 ppmv, could be achieved if international emissions trading, alternative timing of CO_2 targets, and policies that support technology learning in emerging low-carbon technologies are implemented.

The study quantifies the marginal abatement costs of CO_2 mitigation policies that stabilise global CO_2 emissions to levels below 10 GtC/yr by 2050, to vary between 112 and 153 U$/tC in dependence on the policy-modality applied. Also, differences in the discounted cumulative energy system costs of carbon control, including the associated welfare losses (but excluding the benefits accrued from the mitigation of atmospheric carbon) are remarkable for a range of policy-scenarios. The costs are bounded below 1.4% of the Baseline energy-system cost if efficient policies are followed. Otherwise, non-efficient policies, e.g., absence of global carbon permits trade, could increase the cumulative costs to more than 2.6%. Clearly, these results depend on the particular Baseline scenario used, as well as specific assumptions about energy-technology dynamics, but the magnitude of these differences illustrate the benefits that flexible mitigation strategies might offer. The cost-related findings presented in this chapter are in agreement with results from similar studies analysing the effects of imposing a target to stabilise CO_2 concentration in the atmosphere at 550 ppmv (e.g., Labriet et al., 2005).

Three types of policies that would increase the flexibility of global CO_2 mitigation and reduce associated costs are identified as follows:

- *Trade of emissions permits or the “where” flexibility:* International trading of emission permits benefits from efficient CO_2 abatement options across the world and contributes to a significant reduction in carbon control cost. Implementing international co-operation agreements to achieve climate-policy goals, however, appears to represent a challenging policy task. Specifically, the participation of developing countries, where a number of development concerns other than climate change have priority in the policy-making agenda, appears to be difficult. For instance, bringing developing regions that rely on cheap coal resources (e.g., China and India) to accept emission reduction obligations will not be easy. Furthermore, carbon-mitigation targets imposed on the developing regions have to be defined carefully, while respecting regional social and economic conditions. Assigning generous CO_2 emission quotas to these countries may alleviate the attendant costs of emission reduction, by allowing the sales of emissions permits. It remains as a future scope for the analysis to identify which strategies and international coalitions could be more effective and to explore the ancillary benefits of policies that reduce the risk of climate change.

- *Optimal timing or the "when" flexibility:* Optimal timing (or the "when" flexibility) identifies a cost-optimal path in imposed CO_2 reduction targets and can produce additional reductions of 15% in the total system cost as compared to the "where" flexibility policy option. Although the gains resulting from this simulation are not substantial, since the CO_2 targets imposed by the CO_2-cap&trade scenario and the optimal path in emission reduction estimated by the cumulative constraint are similar, the results of the analysis reported herein illustrate the need to search for optimal timing paths in reducing global CO_2 emissions. Moreover, the potential impacts of the "when" flexibility might be more pronounced if the time horizon modelled is extended to 100 years or beyond. Optimal CO_2 mitigation paths should allow for a smooth and cost-effective transition to a low-carbon global energy system, such that an adequate balance is cast between: a) the gradual phase-out of carbon-intensive technologies and, b) the necessary improvement of technical and economic performance of low-carbon emerging technologies and their introduction into the marketplace.

- *Demonstration and deployment of new, low-carbon technologies:* A carbon-mitigation target, as defined in this study, induces important shifts in the energy system towards less carbon-intensive technologies and fuels, e.g., nuclear energy and renewables. Advanced coal-based systems equipped with CO_2-capture penetrate the electricity market and play an important role in carbon abatement. The results reported herein indicate that endogenized technology learning substantially reduces the overall cost of CO_2 mitigation policies; reduction of up to approximately 40% is indicated. Although models with perfect foresight may indicate that low-carbon energy technologies with promising learning potential would become competitive in the long term, this expectation, however, is probably unrealistic when "real-world" markets are considered. Emerging low-emission technologies (e.g., photovoltaic and fuel-cell systems) at the present stage of development are expensive when compared to conventional fossil-based systems. Furthermore, because knowledge cannot be fully appropriated, short-term-oriented markets are likely to under-invest in those technologies. Market experience, however, is an important factor driving cost and performance improvements of new technologies. Moreover, technological progress requires a substantial amount of time. The introduction of policies to support the demonstration and deployment of low-carbon technologies (e.g., learning investments and niche markets), therefore, is a prerequisite to stimulate their learning process and their successful introduction to the marketplace (PCAST, 1999).

The climate-response policies analysed in this chapter can be extended to consider other non-CO_2 greenhouse gases for studying the "what" flexibility in GHG-mitigation. The non-CO_2 GHGs are incorporated in GMM using marginal abatement cost curves (MACs) and the potential implications of abating an optimal mix of GHGs are presented in the consecutive Chapter 6. Additionally, it becomes necessary to identify and quantify the synergies that could exist between climate change policies and other sustainable-development policies. These synergies and ancillary benefits might be particularly important for the developing world relying on carbon-intensive fossil fuels (Beg, et al., 2002). Impact assessment of combined policies that address climate change together with other sustainability issues is provided in Chapter 9.

6. The role of non-CO_2 greenhouse gases in flexible climate-response policies

Consideration of non-CO_2 greenhouse gases (GHG) is an important aspect when examining cost-effective strategies for mitigation of global climate change (e.g., Manne and Richels, 2000, 2004; Reilly et al., 2003). Although CO_2 is the most significant contributor to the human-induced climate change, other GHGs also play an important role, in particular due to the fact that they are associated with a much more potent greenhouse effect in the atmosphere than CO_2. Including non-CO_2 GHGs may have noticeable effects on the costs and composition of mitigation strategies. These gases, therefore, represent an important component when it comes to enhancing the degree of flexibility of climate-change mitigation strategies.

Flexibility is an important attribute of climate-change mitigation policies, particularly if the induced costs and the difficulties of reaching co-operative international agreements are taken into consideration. Different aspects of flexibility in climate-change policies have been highlighted in Chapter 5 in relation to the timing ("when" flexibility) and geographical distribution ("where" flexibility) associated with the CO_2 emissions mitigation strategy. An additional aspect of flexibility is related to technological pathways that could increase the ability of the global energy system to reach significant emission reductions in the long run (Hoffert *et al.*, 2002; Nakićenović, 2003). Consideration of non-CO_2 GHGs introduces another flexibility option referred to as "what" flexibility, i.e., the ability to abate the most cost-efficient mix of GHGs in a given time period. The Kyoto protocol identifies six substances that can contribute to reaching the overall GHG mitigation goal. In addition to CO_2, the Kyoto-gases include methane (CH_4), nitrous oxide (N_2O), and the group of three fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (UNFCCC, 1999).

As is illustrated in Figure 27, the non-CO_2 GHGs, if weighted by their global warming potentials (GWP), represent about 30% of the current global budget of anthropogenic carbon-equivalent (C-eq) emissions (IEA, 2004c). The majority of non-CO_2 GHGs originates from the agriculture and energy sectors, followed by industrial processes and waste treatment. Although the CO_2 emissions associated with the fossil-fuel combustion represent the far largest contribution to the total GHG emission levels (63%), ignoring other Kyoto-gases would lead to the abandonment of a range of cost-efficient abatement options and potential gains because of substitution among gases.

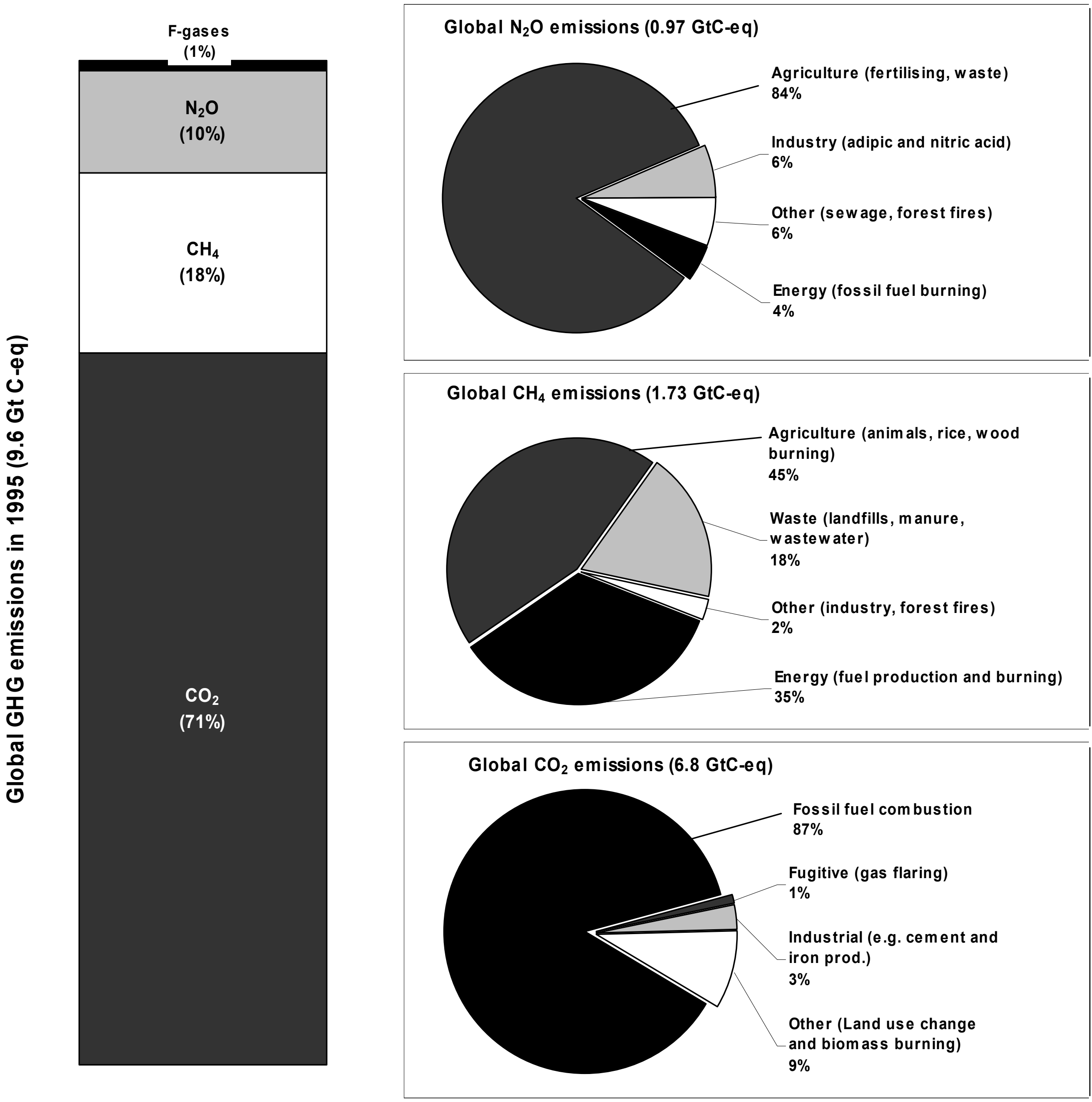

Figure 27. *Shares of global greenhouse gas emissions in 1995 by emission species and by sources of origin. Source: IEA (2004c) and the EDGAR 3.2 database reported by Olivier and Berdowski (2001).*

Several studies have analysed the implications of multi-gas abatement strategies for the Kyoto protocol, for example, Reilly et al. (1999), Burniax (2000) or Lucas et al. (2002), suggesting the reduction in total cost of implementing the Kyoto protocol to be within a range of 26% to 60% relative to policies that assume cuts only in CO_2 emissions. In this context, it is relevant to assess impacts of "what" flexibility in reaching the long-term post-Kyoto GHG-emission stabilisation targets, as defined in previous chapter.

Several possibilities for considering the effects of non-CO_2 GHG abatement in a "bottom-up" modelling framework can be identified. One possibility is the explicit inclusion of abatement technologies, which is an approach that has been followed by Rao and Riahi (2004) and Delhotal et al., (2004), among others. This approach requires the incorporation of abatement systems and mitigation options per emission source for all non-CO_2 Kyoto-gases directly into models in the same way as those for CO_2 reductions. Bottom-up representation of mitigation technologies defines cost and performance characteristics for a number of existing and future abatement systems and processes (e.g., capturing of methane in coal mines and from landfills, limiting the CH_4 leakages from natural gas pipelines, etc.)

The second approach is the use of aggregate marginal abatement cost (MAC) curves that are built on the basis of a detailed bottom-up assessment of abatement technologies. In this case, the MAC curve defines the supply of GHG abatement opportunities as a function of cost, and the resulting function is nothing else but a summary representation of the detailed engineering analysis of a range of abatement technology options. Here, following the work of Manne and Richels (2000, 2004) and Turton and Barreto (2004), MAC curves for the two most important non-CO_2 greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O), are incorporated in the GMM model while considering both energy-related and non-energy-related sources of these gases. By implementing MAC curves for these non-CO_2 GHGs, the scope for the examination of energy-technology strategies in the GMM modelling framework is substantially expanded.

The modelling results reported herein are mainly based on Rafaj et al. (2005c) and illustrate the effects of including these non-CO_2 GHGs on the composition of mitigation strategies and associated costs, while highlighting the importance of the "what" flexibility in climate-change policies. The attention is also drawn to the potential synergies between CO_2 and non-CO_2 GHG abatement efforts in the energy system. In addition, the influence of assumptions regarding technological change in non-CO_2 abatement potentials on the quantification of GHG mitigation strategies is emphasized.

The remainder of this chapter is organized as follows. Section 6.1 presents both the approach to and the limitations of incorporating the MAC curves into the GMM model. Section 6.2 portrays the main characteristics of the illustrative policy scenarios for GHG abatement used in this study. Section 6.3 discusses selected results and illustrates the influence of the inclusion of the non-CO_2 gases in the composition and costs of mitigation strategies. Additionally, a parametric analysis exploring impacts of key MAC-curve parameters is provided. Finally, Section 6.4 outlines some conclusions from this analysis.

6.1. Description of the MAC approach

In this section, a brief description of the approach adopted for incorporating marginal abatement curves in the GMM model is presented. The approach used here is based on the work of Manne and Richels (2004) for the MERGE model and Turton and Barreto (2004) for the ERIS model. This approach uses the regional marginal abatement curves for non-CO_2 GHGs estimated by U.S. EPA (2003).

6.1.1. Definition of baseline emissions

Following U.S. EPA (2003), the categories considered in this analysis are as follows: CH_4 emissions from coal, oil and gas production, solid waste management and manure management, N_2O emissions from adipic and nitric acid production. Baseline emissions must be defined for these different sources of emissions. Baseline emissions can be endogenous if they are linked to a model variable or they can be exogenous if specified from sources external to the model. In this formulation, energy-related methane emissions from coal, oil and gas production are endogenous to the model. Emissions from other sources are exogenous to the model.

Other sources of CH_4 (enteric fermentation and rice paddies) and N_2O (soils) emissions can also be considered exogenously. Since no MAC curves are specified for these gases in the U.S. EPA study (2003), they are treated here, however, as non-abatable emissions. It must be noticed that these sources of emissions currently represent a large fraction of the total emissions of these non-CO_2 gases worldwide, as depicted in Figure 27, but uncertainties still abound regarding the potential, costs, and feasibility of implementation of mitigation measures (Reilly et al., 2003).

6.1.2. Definition of marginal abatement cost curves

A MAC curve typically represents the additional cost of reducing or abating the last unit of a given emittant. Any emission reduction for a gas and for a region can be represented as a point on the associated MAC curve. If several gases are allowed to contribute simulaneously to emission reductions in a given region, and if the marginal costs associated with those reductions are different, the aggregate cost of meeting the reduction target will be lower to the extent that a gas with higher marginal costs of abatement can be substituted for a gas that is less costly to abate. The difference in the marginal costs associated with each substitutable gas can create a potential gain (reduction) in total cost for the same volume of GHG reduction because of the increased supply of new or cheaper abatement opportunities. Considering the local circumstances and the different regional abatement potentials for selected GHGs, the potential trade-off between gases is affected by the location of the emission reduction.

Figure 28 illustrates the gains from abating a portfolio of multiple GHGs relative to the CO_2-only abatement in a region R in time T. The point P1 on the CO_2-only-MAC curve represents the marginal cost C1 of abating an additional unit of carbon equivalents (C-eq) at the abatement quantity A1. Assuming the A1 to be a policy constraint imposed on region R, the same quantity of emission reduction A2 is achieved in the multi-gas abatement strategy at the lower marginal cost C2. The integral under the MAC curves (hatched area) represents the total abatement cost for region R of C-eq emission reduction A1=A2 at time T.

It has to be stressed that MAC curves, as specified in GMM, only represent direct costs of emission-abatement options that are derived from the underlying bottom-up data, thus, there is no direct link to producer and consumer surpluses discussed in Section 3.4.

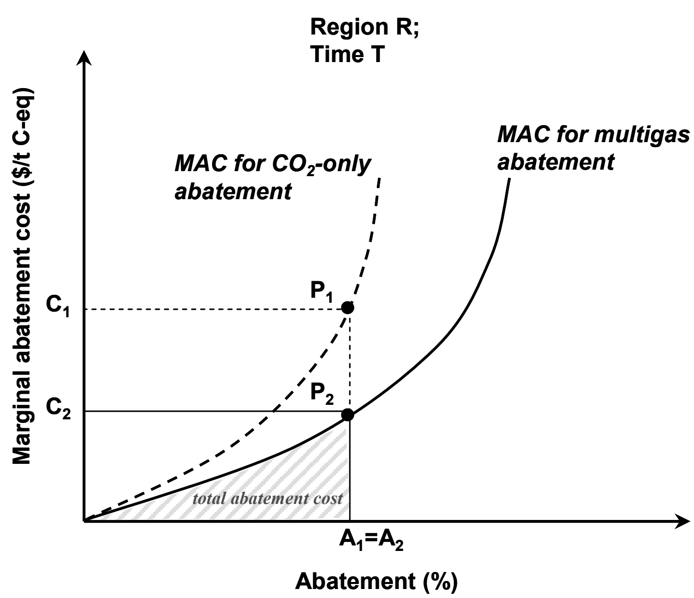

Figure 28. *Illustration of the effect of multigas abatement strategy using the MACs approach.*

The MAC curves are introduced to the GMM model as stepwise curves relating abatement costs and abatement potentials. These abatement potentials are given either as absolute potentials (e.g., in tons of the respective GHG or carbon-equivalent) or in relative terms (e.g., percentage) of a given baseline. In what follows, it is assumed that the abatement potentials are given as a fraction of the baseline and that emissions from non-CO_2 GHG are expressed in terms of carbon-equivalent (C-eq) emissions using the 100-years global warming potentials (GWP) reported by IPCC (2001b), namely 23 for CH_4 and 296 for N_2O. Correspondingly, marginal abatement costs are given in US$/ton C-eq. The use of global warming potentials for assessing the multi-gas mitigation strategies has been criticized in the literature because GWPs do not constitute an adequate "exchange rate" between GHGs (O'Neill, 2000; Manne and Richels, 2000; Fuglestvedt et al., 2003). Specifically, this approach fails to capture a number of physical and chemical interactions between GHGs, as well as differences in persistence in the atmosphere, among other shortcommings. Also, the use of GWP lacks an economic rationale. However, the use of alternative economic indices proposed in the literature, which rely mostly on the monetization of damages caused by climate change, has not been possible so far given the huge uncertainties that currently surround the assessment of climate damages (Reilly et al., 2003).

The abatement potentials have been derived on the basis of considerations of availability, reduction efficiency and technical and economic applicability of the different abatement options (Delhotal et al., 2003). Abatement potentials per price step (i.e., price increment), region, and GHG are specified for a reference time period, here chosen as 2010. 'No-regrets' options were not considered in this specification. That is, all MAC curves were shifted upwards such that abatement costs are always positive. Abatement potentials for other periods are computed using the so-called technical-progress multipliers (*tm*). These multipliers attempt to model possible improvements in abatement technologies occuring over time, thereby increasing the abatement potential achievable at a given cost. These technical-progress multipliers allow extrapolating the MAC curves beyond the reference year (2010), as depicted in Figure 29.

It should be recognized that these technical-progress multipliers provide only a rudimentary representation of technical change in non-CO_2 abatement options and that this representation is made only exogenously (i.e., it does not depend on the amount of cumulative abatement). Moreover, at this point the choice of *tm* values is somewhat arbitrary and dependent on the modeller's judgement. Delhotal et al. (2003) have proposed a methodology for shifting the

MAC curves into the future on the basis of technology assessment for individual technologies, but values are not yet available for multiple regions and/or sectors.

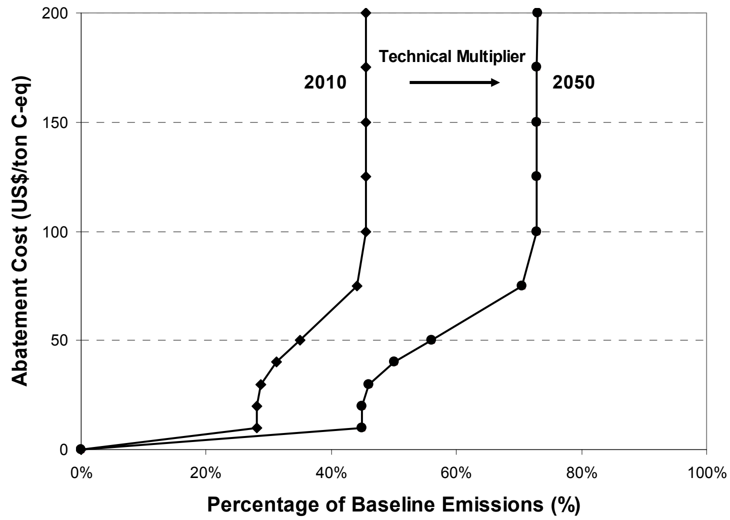

Figure 29. *Illustration of the effect of technical multipliers to shift MAC curves out into future periods.*

6.1.3. Computation of abatement and remaining emissions

In what follows, the basic equations of the MAC curve formulation in the GMM model are described. The following notation is used here for sets, parameters and variables:

Sets

GHG:	GHG emissions category
ERGHG:	Energy-related GHG emissions (a subset of GHG)
NERGHG:	Non-energy-related GHG emissions (a subset of GHG)
MSTEP:	Step of the MAC
REG:	Region
TP:	Time period

Parameters

$abtpref_{GHG,REG,TP}$:	Abatement potential for the reference period (percentage)
$abatepot_{GHG,REG,TP}$:	Abatement potential for other periods (percentage)
$bline_{NERHG,REG,TP}$:	Exogenous baseline emissions for non-energy-related GHGs
$tm_{GHG,REG,TP}$:	Technical multipliers
$gr_{GHG,REG,TP}$:	Growth rate
$seed_{GHG,REG}$:	Seed value for initial GHG abatement
Δt:	Period length
GWP_{GHG}:	Global Warming Potential of a given GHG

Variables

$EMGHG_{GHG,REG,TP}$:	GHG emissions per GHG category, region and time period

$EREM_{ERGHG,REG,TP}$: Baseline energy-related GHG emissions per ERGHG category, region and time period
$ABATE_{GHG,REG,TP}$: Abatement per GHG category, region and time period
$CEQEM_{REG,TP}$: Carbon-equivalent emissions (CO_2+CH_4+N_2O)

The abatement potentials for time periods beyond the reference period (in this case 2010) are defined as the abatement potential for the reference period multiplied by the corresponding technical-progress multipliers:

$$abatepot_{GHG,REG,TP} = tm_{GHG,REG,TP} * abtpref_{GHG,REG,TP} \tag{13}$$

The baseline energy-related emissions ($EREM_{ERGHG,REG,TP}$) are computed as a function of the related activity variables in the model (in this case CH_4 emissions from coal, oil and gas production). Notice that the corresponding emission coefficients may be reduced over time if, for instance, a reduction of leakage in pipelines is assumed.

The amount of abatement per period, region and sector is constrained to (for energy-related and non-energy-related emissions respectively):

$$ABATE_{ERGHG,MSTEP,REG,TP} \leq abatepot_{ERGHG,MSTEP,REG,TP} * EREM_{ERGHG,REG,TP} \tag{14}$$

$$ABATE_{NERGHG,MSTEP,REG,TP} \leq abatepot_{NERGHG,MSTEP,REG,TP} * bline_{NERGHG,REG,TP} \tag{15}$$

The resulting energy-related emissions are computed as the endogenous baseline emissions minus the corresponding abatement as follows:

$$EMGHG_{ERGHG,REG,TP} = EREM_{ERGHG,REG,TP} - \sum_{MSTEP} ABATE_{ERGHG,MSTEP,REG,TP} \tag{16}$$

Similarly, the resulting non-energy-related emissions are computed as the exogenous baseline emissions minus the corresponding abatement:

$$EMGHG_{NERGHG,REG,TP} = bline_{NERGHG,REG,TP} - \sum_{MSTEP} ABATE_{NERGHG,MSTEP,REG,TP} \tag{17}$$

The carbon-equivalent (C-eq) emissions are computed as:

$$CEQEM_{REG,TP} = \sum_{GHG} GWP_{GHG} * EMGHG_{GHG,REG,TP} \tag{18}$$

In order to avoid abrupt changes in non-CO_2 emissions as a result of cost-effective abatement, a maximum growth constraint has been introduced for the abatement of non-CO_2 GHGs. This constraint also reflects the fact that, in reality, abatement technologies will experience a diffusion process that takes time and, thus, their abatement potential cannot be tapped fully at once. As illustrated below in Section 6.3.4, this constraint plays an important role in the level of non-CO_2 abatement in this MAC-curve implementation.

$$\sum_{MSTEP} ABATE_{GHG,REG,TP} \leq \left[\sum_{MSTEP} ABATE_{GHG,REG,TP-1} \right] * (1+gr)^{\Delta t} + seed_{GHG,REG} \qquad (19)$$

This approach also allows for trade of C-eq emission permits across regions. Although emission trading has been discussed mainly for CO_2 in Chapter 5, it is likely that under the multi-gas mitigation strategy it would be extended to other GHGs as well. The complete description of the source code used for implementation of MACs in the GMM model together with underlying assumptions on MAC curves and baseline-emissions are presented in detail in Barreto et al. (2004).

6.1.4. Limitations

As discussed earlier (Section 6.1.1), the MAC-curve approach can be extended to the anthropogenic GHG emission sources generated from other economic sectors, i.e., industry, agriculture or forestry. In this case, the abatement options and related costs have to be associated to the activity of the respective sector to reflect the impact on supply and demand resulting from an abatement activity. This approach is applicable to models that allow for the full economy feedback from all sectors, such as computable general equilibrium (CGE) models (Hyman et al., 2003; Bernard et al., 2004). Since GMM is a partial-equilibrium model describing only the energy sector, the analysis focuses on the energy-related GHG emissions. The MAC curves for CH_4 and N_2O emissions from solid waste management, manure management, adipic and nitric acid production, however, are included for illustrative purposes.

Inclusion of CH_4 emissions from fossil-fuel production, handling and transmission, as implemented in this study, accounts for approximately 80% of the total non-CO_2 GHG emissions from the energy sector (Olivier and Berdowski, 2001). Because of the paucity of the data, some of the energy-related non-CO_2 GHGs, however, are not considered, e.g., CH_4, N_2O and Fluorinated gases from direct fossil fuel combustion and biomass combustion. Main reasons for exclusion of these emission sources are a) the limited abatement potentials, b) a relatively high level of aggregation of some of the demand sectors in the model, e.g., transport, and c) no MAC curves are provided by U.S. EPA (2003) for the GHGs in question.

6.2. Scenarios

A set of four illustrative policy scenarios, as summarised in Table 13, is adopted herein over the Baseline development (see Chapter 4) to provide insights into the role of non-CO_2 gases in the global GHG mitigation strategy.

The first scenario refers to the CO_2-cap&trade scenario described in detail in Section 5.1. In summary, this scenario envisages a global implementation of Kyoto-type flexibility mechanisms to achieve a long-term smooth stabilisation of CO_2 emissions below 10 GtC/yr by the year 2050. The regions OOECD and EEFSU start to apply the prescribed reduction targets from 2010, while the NAME region adopts mitigation target from 2020 onwards. Developing regions (ASIA and LAFM) join the mitigation and trading regime in 2020, and it is assumed that by ~2030 the increase in emissions from developing regions must at most be equal to the reduction of the Annex-B countries. Inter-regional trading of carbon permits allows for “where” flexibility in CO_2 abatement.

Regional reduction targets that take into account emissions of non-CO_2 gases apply in the Multigas-cap&trade scenario. Sources of CH_4 and N_2O emissions comprise fossil fuels production, solid waste management, manure management, and adipic and nitric acid production. The regional distribution of GHG emission reduction entitlements, based on GWP-weighted carbon-equivalents (C-eq), follows the same approach as used in the CO_2-cap&trade scenario.

Although the relative reduction in C-eq emissions in the Multigas-cap&trade scenario over the Baseline is equal to the relative decrease in CO_2 emissions in the CO_2-cap&trade scenario, in absolute terms the amount of emissions that has to be avoided is higher proportionally to the higher level of the Baseline emissions of all GHGs (see Figure 30). The reduction targets can be achieved by curbing emissions of both CO_2 and non-CO_2 gases and at the same time the regions are allowed to trade C-eq permits. This scenario refers to a ‘cap-and-trade’ policy assuming a “where + what” flexibility in GHG abatement.

To emphasize the contribution of non-CO_2 Kyoto-gases in the multi-gas mitigation strategy, the Multigas (CO_2-only)-cap&trade scenario is designed so that the same GHG emission reduction targets as in the Multigas-cap&trade scenario have to be fulfilled while only CO_2 emissions can be reduced and only CO_2-emission permits are allowed for inter-regional trading. Thus, only the “where” flexibility is foreseen in this scenario.

Finally, the fourth scenario CUM-Multigas-cap&trade is defined by a cumulative global C-eq constraint equal to the integral of regional C-eq emission targets up to 2050 as is prescribed by the Multigas-cap&trade scenario. This illustrative cumulative constraint of the CUM-Multigas-cap&trade scenario helps to identify an optimal timing in the global C-eq abatement, while simultaneously allowing for mitigation of all GHGs considered and inter-regional trading of C-eq permits. This scenario provides a full "where + what + when" flexibility in achieving the C-eq mitigation goals.

In all scenarios reported herein, the ETL option is active for a set of electricity generation technologies as specified in Section 3.3.

Scenario	Description	GHG allowed for abatement	Flexibility
Baseline	No long-term global reduction target		
CO_2-cap&trade	Regionalised CO_2 reduction target, Trade of CO_2 permits	CO_2	"where"
Multigas-cap&trade	Regionalised C-eq reduction target, Trade of C-eq permits	CO_2, CH_4, N_2O	"where + what"
Multigas (CO_2-only)-cap&trade	Regionalised C-eq reduction target as above, Trade of CO_2 permits	CO_2	"where"
CUM-Multigas-cap&trade	Global cumulative C-eq reduction target, Trade of C-eq permits	CO_2, CH_4, N_2O	"where + what + when"

Table 13. *Naming and description of the multi-gas abatement policy scenarios.*

One of the consequences of the inclusion of non-CO_2 gases in the mitigation strategy is that the level of "hot air"[4] in the Multigas-cap&trade scenario increases by 20 % as compared to the CO_2-cap&trade scenario due to a drop in energy-related CH_4 emissions in the EEFSU region in 2010 relative to the levels in 1990. Burniax (2000) projects the contribution of non-CO_2 gases to the total amount of "hot air" to be around 90 Mt C-eq. In this analysis, only 50% of the total available "hot air" is allowed for trading between OOECD and EEFSU regions in 2010 (see discussion in Section 5.1.2).

For the Multigas-cap&trade scenario reported in Section 6.3, a maximum annual growth rate for non-CO_2 gases abatement of 10%/yr and the seed value for initial abatement of 5 MtC-eq for all CH_4 and N_2O sources are assumed (Equation 19). For simplicity, a common technical-progress multiplier has been applied across all non-CO_2 GHG-emission categories projecting a 5% total increase in abatement potential by 2050 over the MAC reference year 2010 (Equation 13). This somewhat conservative assumption is made to avoid unrealistic levels of GHGs reduction by 2050, since the abatement potentials assumed by U.S. EPA (2003) for the

[4] In the context of the Kyoto protocol "hot air" represents a gap between projected GHG emission levels and prescribed emission reduction targets for Annex-B countries of EEFSU during the 2008/2012 commitment period.

year 2010 are already significant, and because of uncertainties related to technical change in abatement options. To illustrate the influence of aforementioned parameters on the cost and composition of multi-gas mitigation strategy, a parametric analysis has been performed and is reported in Section 6.3.4.

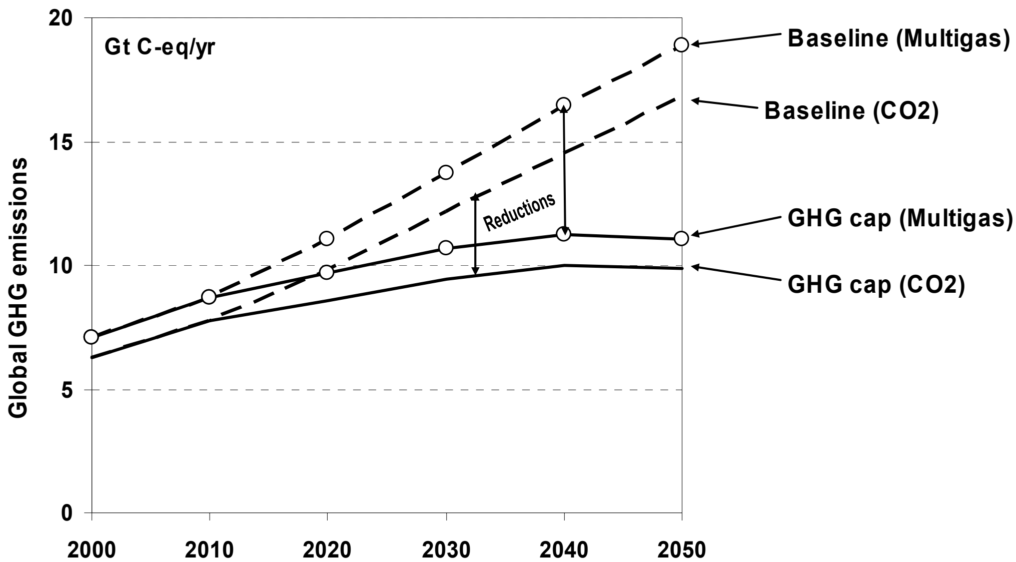

Figure 30. *Global GHG emissions (CO_2, CH_4, N_2O) in the Baseline scenarios and the reduction targets in the CO_2- and Multigas-mitigation scenarios. CO_2 here refers only to energy-related emissions.*

6.3. Scenario Results

The results provided here describe implications of policies that include abatement of non-CO_2 GHGs in the portfolio of mitigation strategies summarised in Table 13. The structural changes in the global electricity sector are portrayed in detail and the role of power generation technologies that contribute the most to GHG reduction, i.e., CO_2-capture, nuclear plants and renewables, under different flexibility regimes is highlighted. The composition of GHG-reducing components is compared for CO_2-only and multi-gas scenarios. The potential synergies between CO_2 and non-CO_2 GHGs abatement efforts are addressed, using the case of methane emissions from fossil-fuel production as an example. The cost impacts are analysed in terms of marginal costs of emission permits and changes in total system cost relative to the Baseline. Finally, a sensitivity analysis explores the influence of selected parameters on the total cost of multi-gas abatement strategy.

Detailed description of changes in the primary energy and final energy consumption are not included in this chapter, since the trends in "what"-flexibility scenarios are similar to those reported in Section 5.2.1 for the CO_2-mitigation scenarios. Moreover, the version of GMM used in this analysis does not provide the full picture of shifts that can occur under the multi-gas mitigation policies. For instance, under a stringent GHG-constraint, it is expected that the methane captured from the coal mines would be utilised for electricity and heat production and could contribute to an overall decrease in coal consumption.

6.3.1. Structural changes

Electricity generation

As shown in Figure 31, imposition of C-eq constraint induces considerable changes to the electricity-generation market regardless of the type of flexibility mechanism used to reach the emission reduction targets. A common trend is observed across the CO_2-cap&trade, Multigas-cap&trade and Multigas (CO_2-only)-cap&trade scenarios as compared to the Baseline development: the amount of power generation based on fossil-fuel combustion undergoes substantial reduction over the time horizon and is balanced by an increased contribution from advanced fossil and carbon-free sources. The substitution effect is most pronounced in the Multigas (CO_2-only)-cap&trade scenario as this scenario implies a more severe reduction target as compared to the CO_2-cap&trade scenario and at the same time excludes CH_4 and N_2O from the portfolio of abatable gases.

While both the CO_2-cap&trade and Multigas (CO_2-only)-cap&trade scenarios allocate similar increases in nuclear and renewable power production between 2010 and 2030, implementation of abatement options for non-CO_2 GHGs in the Multigas-cap&trade scenario reduces significantly the contribution of nuclear energy and renewables over the whole time horizon as the penetration of these technologies is replaced by cheaper options associated with CH_4 and N_2O mitigation. Similarly, the rise in the power production from systems with CO_2-capture is lower in the Multigas-cap&trade scenario relative to the cases where the mitigation efforts involve only the CO_2 emissions reduction.

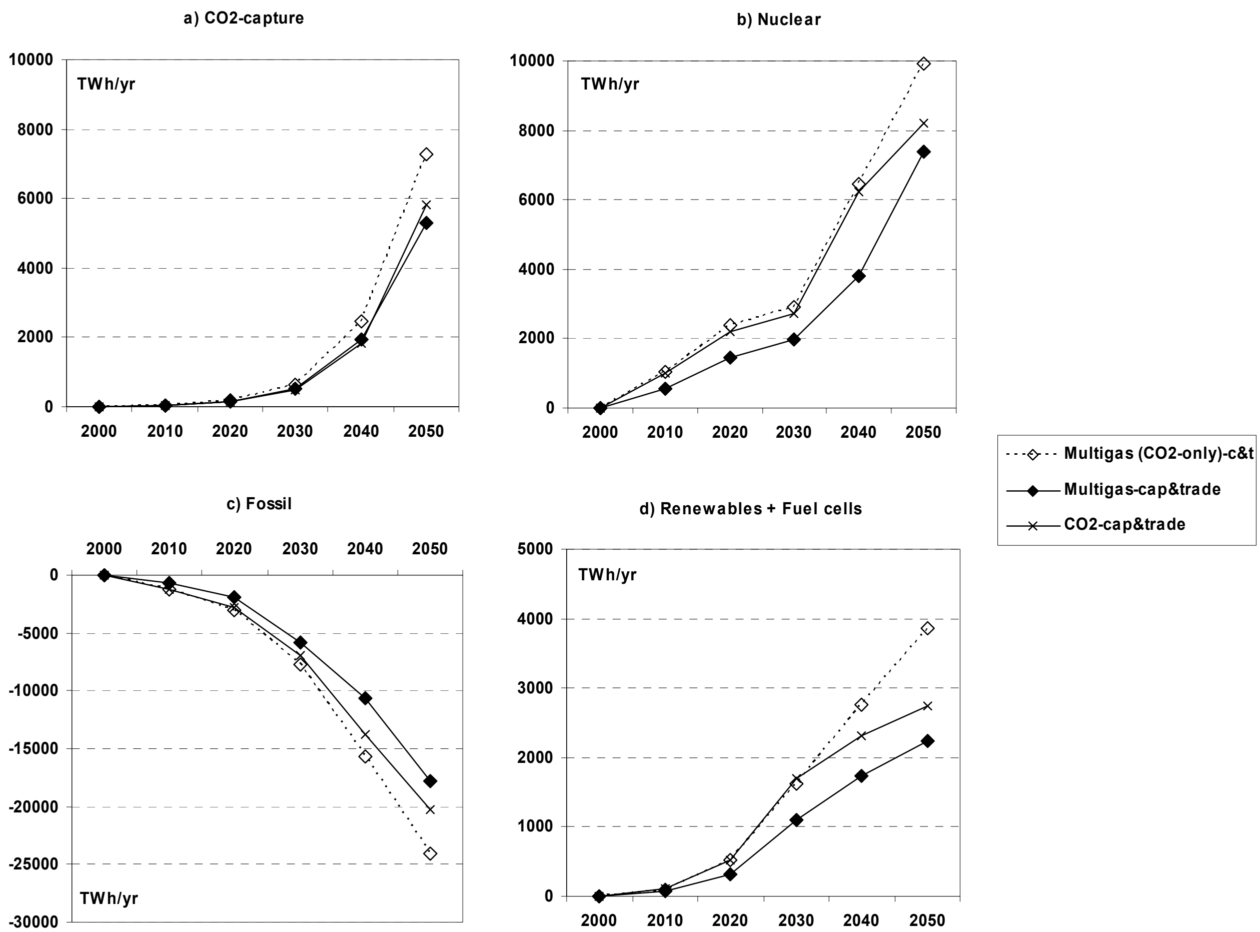

Figure 31. *Change in global electricity generation over the Baseline scenario for C-eq abatement scenarios. a)* ***CO_2-capture*** *aggregates coal and natural gas technologies equipped with carbon capture systems; b)* ***Nuclear*** *refers to conventional and advanced nuclear plants; c)* ***Fossil*** *comprises all generation sources based on combustion of coal, natural gas and oil without CO_2-capture; d)* ***Renewables + Fuell cells*** *graph refers to the aggregated contribution from hydro power, wind, biomass, geothermal, solar electricity and all types of fuel cells.*

Figure 32 illustrates the power generation mix in the year 2050 for the Baseline and for the set of GHG mitigation scenarios. While the power generation in the end of horizon for the Baseline scenario is dominated by conventional and advanced coal systems, natural gas combined cycle (NGCC) becomes the main source of electricity for GHG-constrained scenarios. The only coal-based systems that undergo substantial increase over the Baseline are the advanced coal plants with CO_2-capture and integrated coal gasification combined cycle (IGCC) with CO_2-capture. Penetration of these technologies is the highest in the Multigas (CO_2-only)-cap&trade scenario, and the lowest in the Multigas-cap&trade scenario. The same observation is reported for the generation from nuclear power plants. Differences in the power production from the renewable sources appear at a smaller extend. Generation from the hydropower and both hydrogen and natural gas fuel cells (FC) in the Multigas (CO_2-only)-cap&trade scenario, however, increases remarkably over the Baseline development. Policy implications of these findings are elaborated in the following consecutive sections.

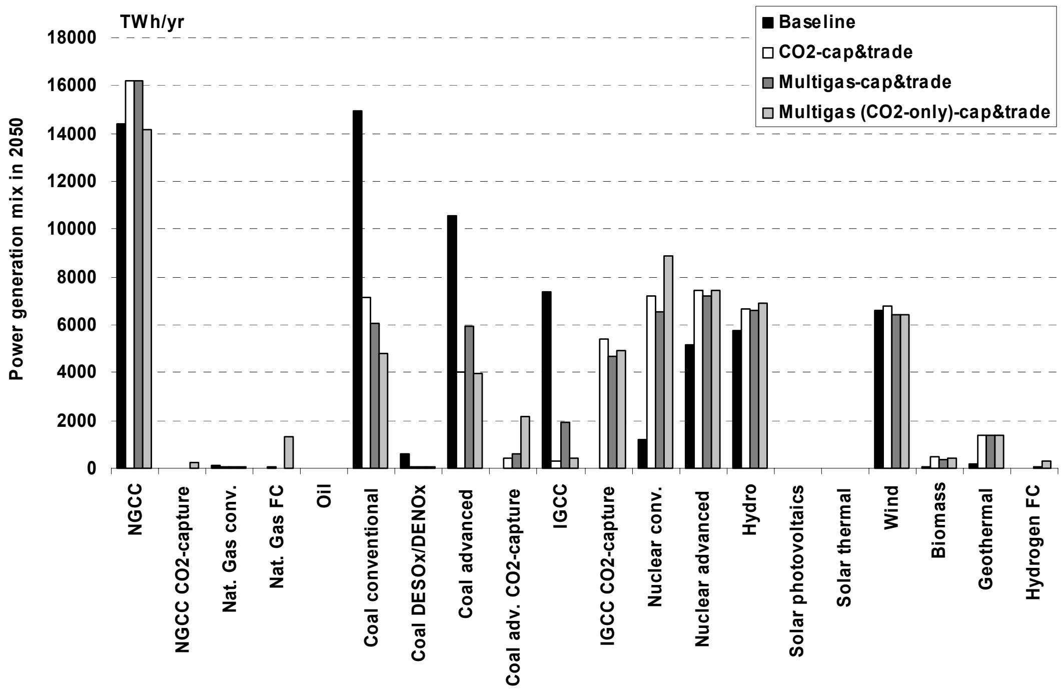

Figure 32. *Contribution of technologies to the global electricity generation mix in 2050 in C-eq constrained scenarios.*

6.3.2. Environmental impacts

6.3.2.1. Global CO_2 emissions

Baseline emissions of the three GHGs considered herein (CO_2+CH_4+N_2O) increase with an annual growth rate of 1.96% until 2050, and reach a level of 18.9 GtC-eq/yr. The annual growth is lowered to 0.9% in the Multigas-cap&trade scenario. By 2030, the total GHG emissions are stabilised to around 11 GtC-eq/yr. The cumulative C-eq reduction during the period 2010-2050 is quantified at 177 GtC-eq.

Figure 33 shows the contribution of non-CO_2- and CO_2-abatement options to the overall C-eq reduction over the Baseline for the Multigas-cap&trade scenario. The fraction of CH_4 and N_2O reduction decreases from 23% in 2020 to 15% in 2050, suggesting that the non-CO_2 GHGs abatement can play a transition role in the GHG mitigation strategy. Energy-related CH_4 emissions contribute 74% of the total non-CO_2 GHG emission reduction in 2050. The contribution of non-energy related CH_4 and N_2O emission abatement in 2050 is 21% and 5%, respectively.

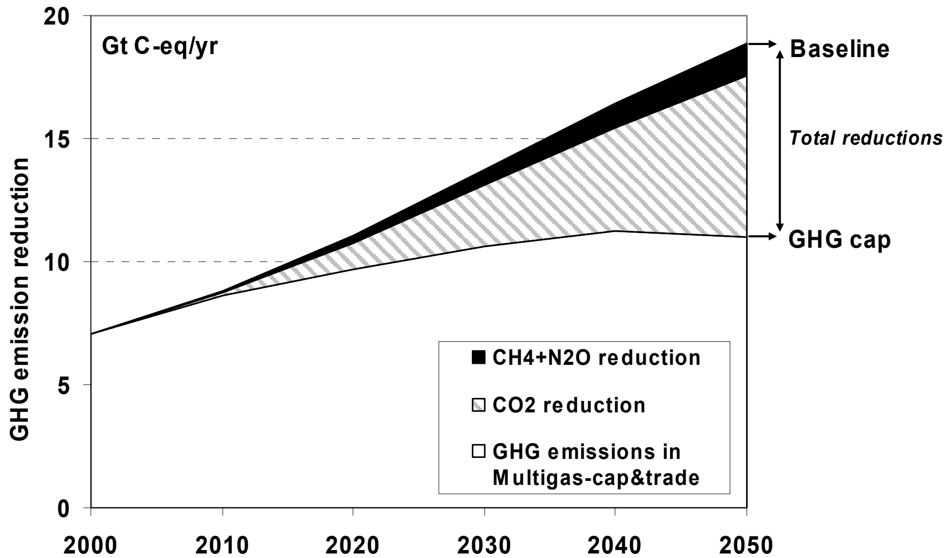

Figure 33. *Multigas emissions reduction under an illustrative Multigas-cap&trade scenario. The contribution of non-CO_2 GHGs to the mitigation is distinguished.*

Change in the global GHG emissions relative to the Baseline in the Multigas-cap&trade scenario and Multigas (CO_2-only)-cap&trade scenario mitigation scenarios is summarised in Figure 34. While energy-related CO_2 emissions are reduced by 35% in 2050 in the Multigas-cap&trade scenario, the methane emissions reach levels that are 60% below the Baseline development. Substantial reductions in N_2O emissions are achieved already by 2020 and further mitigation of N_2O emissions is bounded by the abatement potentials defined by the MAC curves.

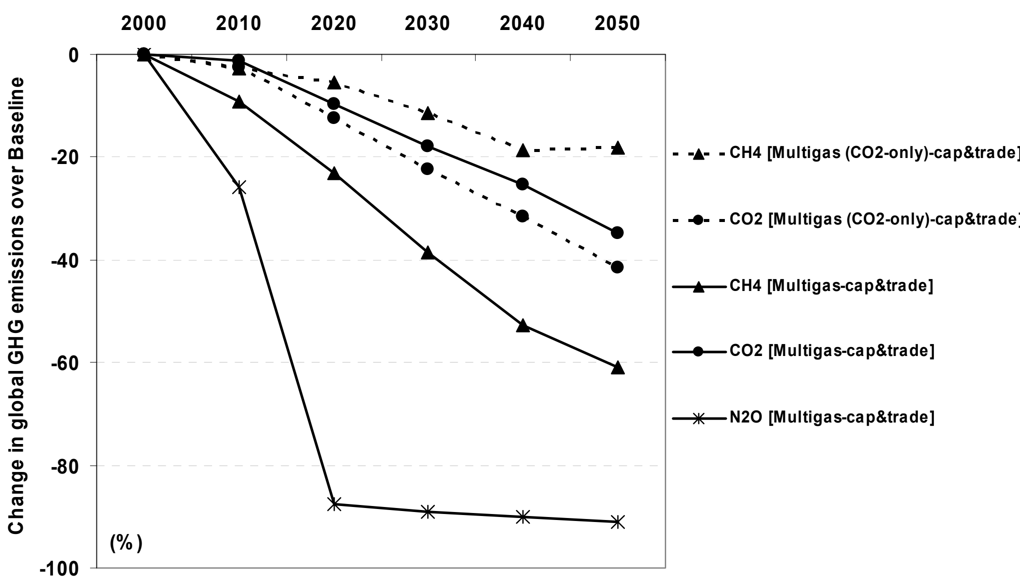

Figure 34. *Change in the global CO_2, CH_4 and N_2O emissions relative to the Baseline in the Multigas-cap&trade scenario and Multigas (CO_2-only)-cap&trade mitigation scenarios.*

Under the Multigas (CO_2-only)-cap&trade scenario, the CO_2 emissions are reduced by 42% relative to the Baseline. Although the reduction target is achieved entirely by mitigation of the CO_2 emissions, some reduction of methane emissions (by 18% in 2050 over the Baseline) already takes place due to significant decrease in the use of fossil fuels. This finding suggests that synergies can be expected between "Kyoto-gases" under C-eq mitigation constraints and at the same time indicates that the C-eq price reported for the CO_2-only scenarios can be overestimated.

6.3.2.2. Break-down of GHG reduction components

The importance of non-CO_2 GHGs abatement in the mitigation strategy is contrasted in the Figure 35, where a break-down of different C-eq reduction components is provided. An inter-fossil fuel switching, e.g., substitution from coal to natural gas, plays the dominant role in the global mitigation process in both the Multigas-cap&trade and Multigas (CO_2-only)-cap&trade scenarios. Important differences are observed, however, for the role of nuclear energy and CO_2-capture. The inclusion of options to abate non-CO_2 GHGs reduces the contribution of nuclear energy by 50% to 25% between 2010 and 2050. Similarly, the CO_2-capture contributes by 26% less to the C-eq reduction in 2050 as compared to the case where only CO_2 emissions can be abated. Implication of this result is that the reduction of non-CO_2 GHGs can shift the need to invest in capital-intensive technologies, e.g., nuclear or CO_2-capture, towards later decades.

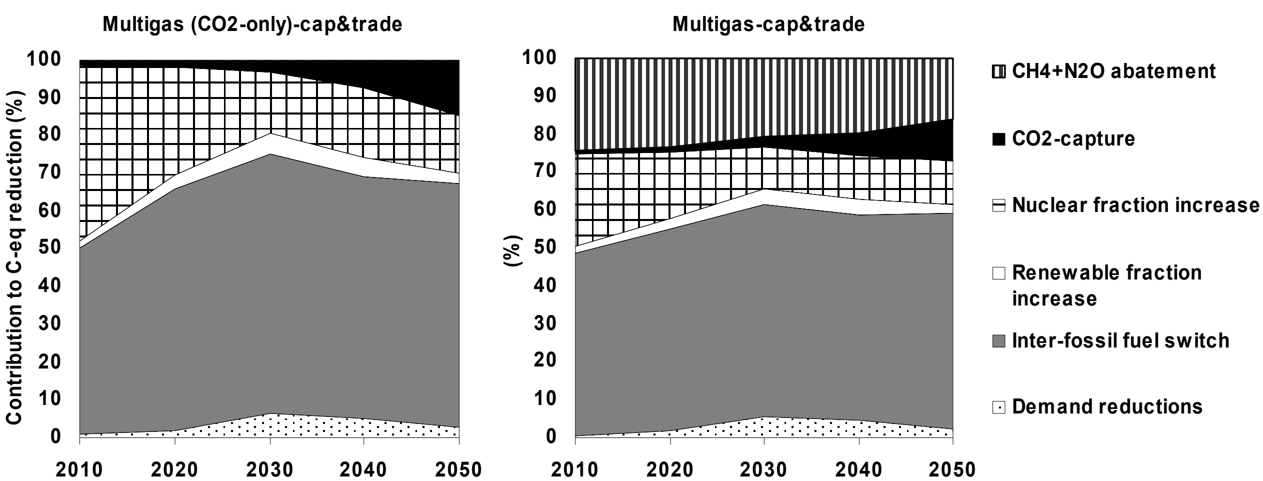

Figure 35. *Break-down of GHG reduction components for the Multigas-cap&trade and Multigas (CO_2-only)-cap&trade scenarios.*

6.3.3. Cost impacts

6.3.3.1. Carbon-equivalent permit price

In all scenarios that consider the "where" flexibility in GHG abatement, the price of C-eq permits globally traded across regions increases over the time horizon, with the exception of the period around 2020. The reduction in marginal cost in this period is associated with the increased supply of C-eq permits originated from Non-Annex-B countries joining the GHG-mitigation and trading regime from 2020 onward. In 2050, the C-eq permit price reaches 145 \$/tC-eq for the CO_2-cap&trade scenario. This price is increased by 16% when the more severe multi-gas mitigation target is applied without possibility to abate non-CO_2 GHGs (i.e., the Multigas (CO_2-only)-cap&trade case).

As shown in Figure 36, inclusion of CH_4 and N_2O in the emission mitigation strategy reduces the marginal price of C-eq relative to the CO_2-only scenario over the time horizon between 7% in 2010 to 28% in 2050. These results are consistent with the observations made above in Section 6.3.1 for the technology dynamics in the electricity sector suggesting that the "what" flexibility can result in important cost reductions by postponing the investments in expensive technologies, e.g., CO_2-capture or nuclear power plants, necessary to reach GHG abatement targets.

Benefits in terms of C-eq price reduction invoked by adopting different flexibility concepts are further pronounced for the CUM-Multigas-cap&trade scenario allowing for a full "where + what + when" flexibility in GHG abatement. The reduction in C-eq permit price over the Multigas (CO_2-only)-cap&trade scenario accounts for 40% and is attributed to the cost-optimality in a) timing of GHG mitigation, b) allocation of abatement possibilities across the world regions, and c) mix of gases available for abatement.

6.3.3.2. Total system cost

Cost impacts of different flexibility modalities associated with global GHG mitigation efforts are demonstrated further in Figure 37 by calculation of the difference between the total discounted system costs and the welfare loss due to demand reductions for the Baseline and C-eq constrained scenarios. The total discounted energy-system cost increases by 1.6% over the Baseline in the CO_2-cap&trade scenario that aims at stabilizing the global energy-related CO_2 emissions at a level of 10 GtC-eq by 2050. Applying the "what" mitigation flexibility in the Multigas-cap&trade scenario reduces the total cost by nearly 10% relative to the CO_2-cap&trade case, although the total amount of C-eq avoided is higher proportionally to the differences in the reference C-eq emissions. Exclusion of the "what" flexibility option in the Multigas-cap&trade scenario results in a total cost increase of 33%. Allowing for the full abatement flexibility in the CUM-Multigas-cap&trade scenario suggests additional gains in moderating the cost penalty related to the GHG policy constraint by 18%.

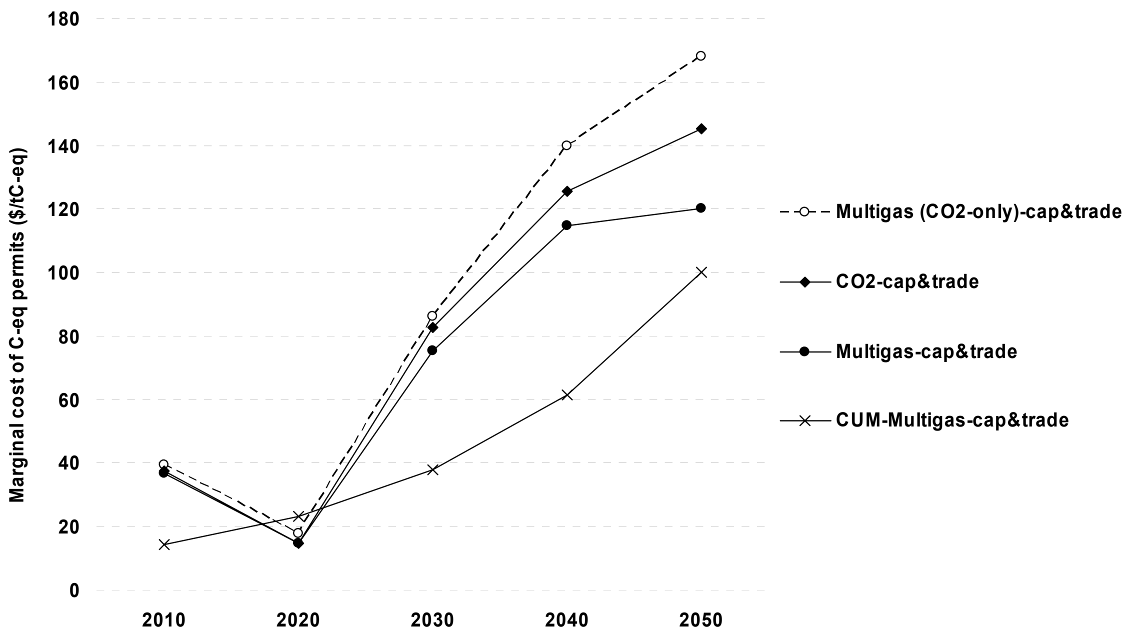

Figure 36. *Marginal cost of C-eq emission permits for scenarios adopting different type of flexibility in the GHG mitigation.*

To put the presented results in the right perspective, it has to be emphasised that a number of factors limit the capability of the approach used for this analysis to seize fully the potential benefits of adopting the climate policies based on the "what" flexibility. First, some sources of the energy related GHGs, e.g., direct fuel combustion, were omitted from the total emission balance because of the lack of data and limited abatement potential for those sources. Secondly, the re-use of methane captured during the abatement processes, e.g., in coal mining, is not modelled in GMM.

Furthermore, with GMM being a partial equilibrium model (energy sector only), inclusion of non-energy related GHGs would require constructing a set of sub-modules able to depict economic impacts of abatement activities in sectors, where the non-energy GHGs originate, i.e., agriculture or industry. Nevertheless, the findings reported herein are in accordance with the studies on multi-gas strategies performed with other "bottom-up" models (Criqui, 2002; Rao and Riahi, 2004).

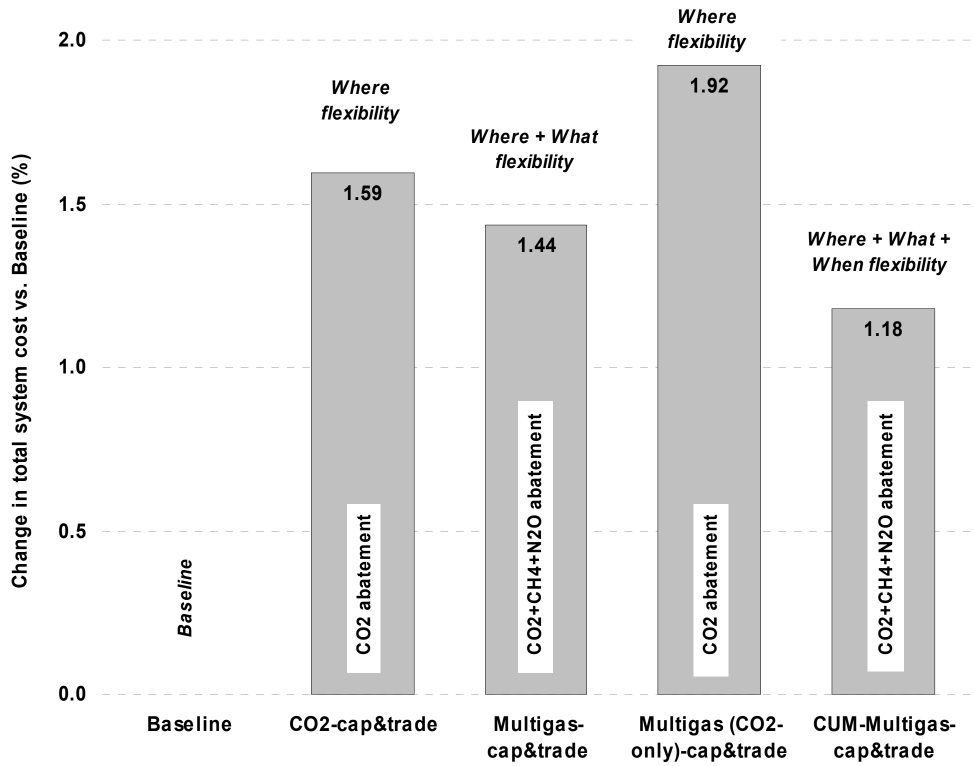

Figure 37. *Change in the cumulative discounted energy system cost and the welfare loss due to demand reductions relative to the Baseline for scenarios adopting different type of flexibility in the GHG mitigation.*

6.3.4. Parametric analysis

The dependence of the mitigation cost and time evolution of energy related methane emissions to the changes in some key parameters for the Multigas-cap&trade scenario is analysed in this section. The parameters under investigation are: a) the seed value of initial non-CO_2 GHGs abatement; b) maximum growth rate for deployment of CH_4 and N_2O abatement options; and c) the technical-progress multipliers.

The first two parameters refer to the maximum growth constraint for non-CO_2 abatement defined in Equation 19. The third parameter is defined in Section 6.1.2. Results presented in the previous sections refer to the *central case* of the Multigas-cap&trade scenario assuming a maximum growth rate of abatement of 10%/year, a seed value of 5 MtC-eq and an abatement potential that increases by 5% in 2050 relative to 2010. Figure 38 shows the impact of key parameters on the change of total systems cost over the Baseline for the Multigas-cap&trade scenario.

Selection of the seed value influences the penetration of the abatement option in the initial period when the option becomes competitive or cost effective. It is particularly important for the multigas abatement strategy, since the role of the non-CO_2 abatement is largest in the first periods of adoption of GHG policy constraint. Figure 38 shows that the increase in the seed value to 20 MtC-eq produces a reduction in total system cost by 14%. For simplicity, a uniform seed value has been used across GHGs and regions. For a model with higher regional resolution, however, the seed value would have to be adjusted to the baseline emission levels of the respective region.

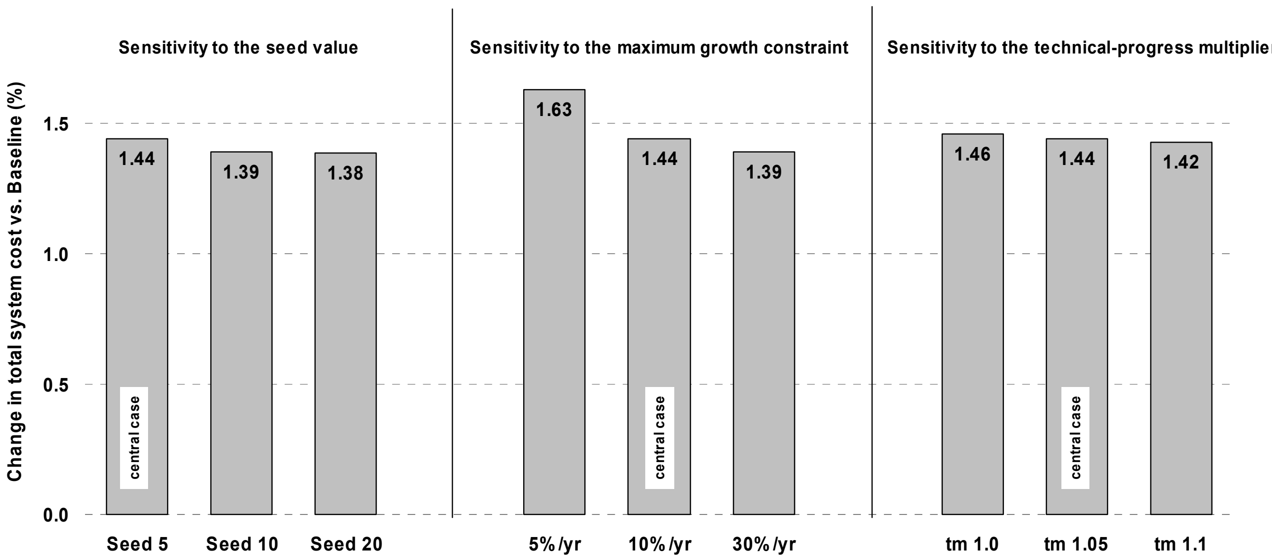

Figure 38. *Comparison of increases in total system costs over the Baseline for selected variants of the Multigas-cap&trade scenario differing on assumptions about the seed value for initial abatement, maximum growth rate of abatement and the technical multipliers.*

The variations in the change of total system cost over the Baseline for the Multigas-cap&trade scenario is most pronounced for the assumptions made for annual growth constraint on CH_4 and N_2O abatement. The increase in the total system cost is by 43% higher relative to the central case when the annual growth rate is halved. This cost increase is associated primarily with investments due to larger penetration of expensive technologies, e.g. nuclear or CO_2-capture, as compared to the cases allowing for faster exploitation of non-CO_2 abatement potential.

Finally, the total system cost changes are compared in Figure 38 as resulting from the modification of technical multipliers (*tm*). In the case where no improvement of abatement technologies over time is foreseen (tm 1.0), the total cost increases by 5% relative to the central case (tm 1.05), and by 10% relative to the case assuming 10% abatement improvement until 2050 (tm 1.1). That is, changes in the total system cost are proportional to the change in the technical progress assumption, which suggests that the abatement potential is fully utilised for all three sensitivity cases.

The time evolution of the global CH_4 emissions from coal and natural gas production in the Baseline and Multigas-cap&trade scenarios with different assumptions on the maximum growth constraint for the penetration of abatement technologies is illustrated in Figure 39. If a growth rate of 30%/yr is assumed, the total emission reduction reaches the abatement potential for the coal production in 2020, and for the natural gas production in 2030.

A smoother reduction for both sources is reported in the case allowing for 10% annual growth, and the abatement potentials are reached in 2040 and in 2050, respectively. Reduction of the growth rates to 5%/yr results in a significantly lower total CH_4 abatement in both sectors, since other systems (CO_2-capture, nuclear power) increase their penetration in order to fulfil the C-eq reduction targets. It has to be mentioned that the uptake of low-carbon power generation technologies is accelerated by 'learning-by-doing' cost reduction effects simulated in the GMM model.

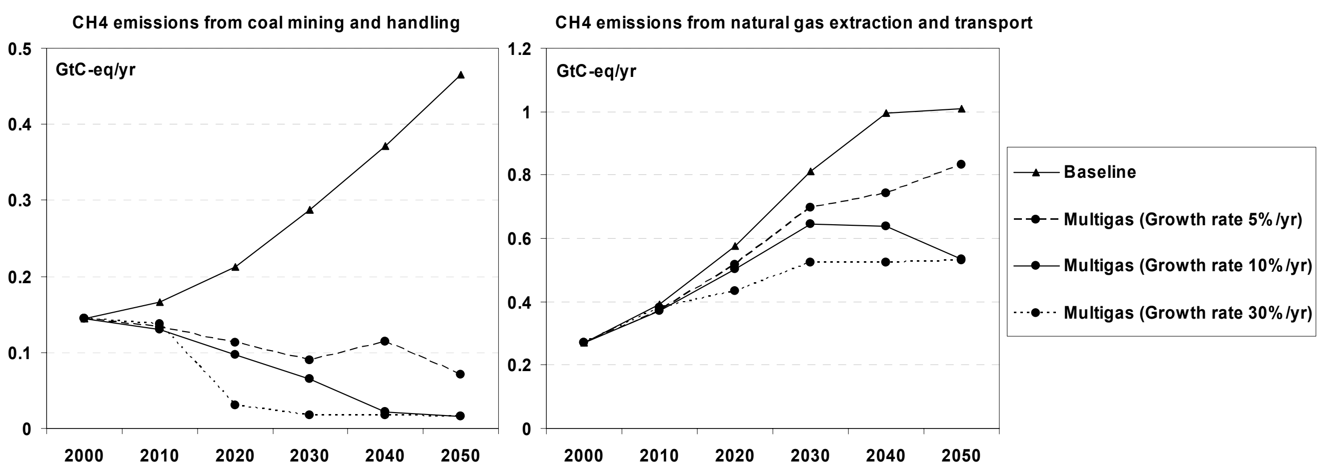

Figure 39. *Influence of the maximum growth constraint of abatement on resulting global methane emissions from coal and natural gas production sectors.*

6.4. Summary and concluding remarks

This chapter has presented an analysis of the effect of non-CO_2 greenhouse gases on the composition and costs of flexible climate policies. Since the global energy system is the focus of this analysis, flexibility as used here refers generally to an ability to change and adapt to new conditions and circumstances invoked by imposition of the GHG mitigation constraint.

The non-CO_2 emission abatement is incorporated in GMM by using marginal abatement cost (MAC) curves for selected sources of energy and non-energy related CH_4 and N_2O emissions. In this approach, the energy related methane emissions from fossil fuels production are modelled endogenously, while methane emissions from solid waste and manure management, as well as N_2O emissions from adipic and nitric acid production, are exogenous to the model.

The role of non-CO_2 gases in strategies aimed at curbing the GHG emissions is demonstrated within a set of policy scenarios adopting different flexibility mechanisms. The CO_2-cap&trade scenario represents a “where” flexibility mechanism allowing for international trading of C-eq permits. The Multigas-cap&trade scenario combines the permit-trade with the “what” flexibility approach allowing for abatement a cost-effective mix of gases. The role of optimal timing in C-eq emission abatement is highlighted in the CUM-Multigas-cap&trade scenario that represents a full “where + what + when” flexibility type of mitigation strategy.

In agreement with similar studies, the results presented here suggest a significant cost-reducing effect associated with the inclusion of non-CO_2 gases in the long-term GHG stabilisation strategies. The total discounted system cost in the Multigas-cap&trade scenario, including the invoked welfare loss, is by 33% higher as compared to the scenario where the “what” flexibility is excluded. On the other hand, allowing for a cost-optimal timing path in the CUM-Multigas-cap&trade scenario produces additional total cost reduction of 18%. In 2050, the marginal cost of the CO_2-cap&trade constraint is esteimated to be 145 $/tC-eq. This marginal cost is reduced to 120 $/tC-eq in the Multigas-cap&trade scenario, although the amount of GHG emissions abated is higher than in the CO_2-cap&trade case.

Abatement of non-CO_2 GHGs contributes by 23 % to the total GWP-weighted GHG emission reduction in 2020 and this fraction decreases to 15% in 2050, suggesting that CO_2 emissions will remain the primary focus of climate-protection efforts. Nevertheless, the abatement of other gases can moderate the cost of stringent C-eq reduction targets by postponing investments in capital-intensive technologies, e.g., nuclear power, renewables or CO_2-capture, towards the later decades.

From the methodological perspective, the application of marginal abatement curves in the “bottom-up” modelling context exhibits a number of limitations the modeller must be aware of and, therefore, should be used carefully. The use of MAC curves, nonetheless, was found to provide a compact and aggregate mechanism for representing the effect of non-CO_2 GHGs in the GMM “bottom-up” model, and the magnitude of cost impacts reported in this chapter indicates the potential benefits that can be expected from inclusion of non-CO_2 GHGs in the climate response policies.

7. Renewable portfolio and subsidy schemes to promote renewable electricity sources

The policy framework under examination in this chapter considers options and addresses impacts of policy instruments that promote the introduction of renewable energy sources and technologies into the electricity market. As described in Section 2.2.4, strategies that aim at the promotion of renewable energy are usually based on regulatory measures, monetary incentives, and international cooperation schemes. Furthermore, these strategies imply policy-actions in favour of learning investments, as well as research, development and demonstration (RD&D) expenditures.

Market-deployment policy instruments that promote renewables can be targeted at different segments of an energy system, e.g., renewable energy suppliers, end-use consumers, new generating capacities or energy production itself. In many instances, the policy instruments simultaneously address more than one of the aforementioned targets (IEA, 2004a). From the broad range of policy tools that have recently been introduced in many countries, two instruments addressing power production on the supply-side of the GMM reference energy system were selected and assessed herein: a renewable portfolio standard, and a subsidy scheme for renewable electricity.

The first element of the renewable-energy policy set investigated envisages an obligation imposed on suppliers to generate an exogenously determined, minimum amount of renewable electricity. This policy instrument is known as *renewable portfolio standard* or *renewable-energy quota system*. The renewable portfolio standard typically requires power utilities to comply with a predefined quantitative target, without precisely specifying the source composition of the renewable-electricity supply. Translated, this means that the least-cost renewable-energy sources are exploited first, which is followed by the engagement of more costly renewable-energy resources. In the case of non-compliance, a penalty can be set for producers that fail to reach the target (IEA, 2004a). The renewable-electricity quotas can be defined by minimum quantity (i.e., TWh/yr or GJ/yr) or by a fraction of total electricity generated, and can be specified at the country or regional levels (see e.g., EC, 1997).

The second policy instrument analysed is the aggregated *subsidy scheme for renewable power production*. In the present electricity markets, the subsidies for renewables are usually not disbursed directly as a payment per unit of output, although an example of this concept exists in the state of California, as is described by Sawin (2004). Renewable electricity is usually subsidized indirectly, for example by using rebates for consumers buying green electricity or, more frequently, by introducing the so-called feed-in tariffs. A feed-in tariff scheme is an incentive pricing-system that grants a guaranteed buy-back rate of electricity originating from renewable-energy sources. This scheme requires electricity utilities to purchase any renewable electricity at a fixed preferential price, with this price being guaranteed for a specified period of time. The price can be determined for each technology by the avoided cost of new generation and is usually covered by the consumer (Wörlen, 2003).

Achieving a considerable contribution from renewable energy sources in the long term, e.g., by 2050, is expected only for a case when the world as a whole participates to efforts directed towards renewable-energy promotion. Implementation of both policy instruments, therefore, is extended globally to all regions defined by the GMM model. It is essential for successful implementation of policies that the renewable electricity generation targets are reached cost-effectively, and that policy instruments allow for some flexibility in meeting the policy goals. Keeping this requirement in mind, *trading of* so-called *green certificates* between world regions is foreseen under these above-described policy options, wherein green-certificate trading would occur between regions having surpluses of renewable electricity and those having limited or expensive renewable-energy options for power generation. Allowing for international trade of “green electricity” under a quota system represents a kind of “cap-and-trade” policy that favours renewable-energy resources.

It must be recognized that neither quotas imposed by a renewable portfolio nor generous subsidies for renewables provide any guarantee that capital-intensive renewable-energy technologies will increase substantially their market share, or that their contribution will be sustained in the long-term perspective. Break-through of costly systems like SPV is conceivable only under policy circumstances balancing the market deployment instruments with investements in emerging systems that help to drive these technologies down their learning curves and thereby to increase their competitiveness against the lower-cost technologies. Furthermore, the attendant policies must assure that the experience gained through installation and operation of renewable-energy generation systems is distributed from one region to another.

The study on policies promoting renewable energy sources reported herein is focused on the following questions:

- What would be the implications of a renewable portfolio standard imposing a constraint on a minimum generation (market) share based on renewable energy sources?
- What is the impact of subsidy schemes that provide a pricing incentive for accelerated penetration of generation technologies based on renewable energy sources?
- How would the results change if countries in a given pool were allowed to trade the green certificates?
- What is the role of policies that support technological learning and diffusion of renewable electricity technologies?

The structure of this chapter is as follows: Section 7.1 provides a description of how the policy instruments studied are translated into energy scenarios in the GMM model, and discusses briefly the assumptions for renewable electricity potentials, as well as elaborating on the specifications for trading of green certificates. Section 7.2 is devoted to the analysis of structural changes invoked by an increased contribution from renewable energy sources. The cost impacts of different policy modalities are discussed in detail. Finally, Section 7.3 summarizes key modelling outcomes and derives some policy-related conclusions.

7.1. Scenarios

7.1.1. Renewable technologies in GMM and their potentials for power generation

Six power generation technologies based on renewable energy sources are defined for each region of the GMM model: hydro-electric plant, solar-photovoltaic (SPV) and solar-thermal electric plants, wind turbine, aggregated biomass power plant, and geothermal electric plant. Table 8 lists cost and performance specifications for each of these renewable power technologies. It is noted that conservative value for the capital investment cost for hydropower is used, since the difference in cost for small and large plants of this genre are not considered.

Two renewable technologies, wind turbines and solar photovoltaic (SPV) systems, are implemented as ‘learning’ technologies, with the investment cost being endogenously determined by the model as a function of cumulative installed capacity according to Equation 1. Learning rates for wind turbines and SPV are given in Table 10. As described in Section

3.3, the endogenous technological learning (ETL) algorithm used in GMM incorporates knowledge spillovers across world regions; the learning performance of a technology in one-region, therefore, influences the speed of learning in all other regions. An underlying assumption in all scenarios, evaluated with the ETL option being active, is that a global spillover of experience and know-how transfer from North to the South will occur uninhibited.

An effective implementation of policy instruments in favour of renewables must take into consideration the availability of renewable energy resources in a given region. Penetration of renewable power generation is controlled in GMM by the imposition of exogenous bounds on both capacity and activity levels, and by annual growth/declination-rates enforced for each technology, as is outlined in Section 3.2. Detailed regional bounds on renewable electricity generation, which correspond to assumed technical potential of a respective technology within the given time framework 2000-2050, are provided in Table 14. Additionally, the large market penetration of intermittent (e.g., wind and SPVs) electricity sources, which might interfere with the power-network stability, is addressed by a constraint that restricts the maximum amount of generation from these technologies.

7.1.2. Renewable portfolio standard

A policy instrument of imposing an obligation to generate a specified fraction of renewable electricity, also called the Renewable portfolio standard, requires from the power suppliers to include a minimum share of renewable energy into the supply mix. Scenarios presented herein force the renewable electricity sources, including large hydro power plants, to contribute in each region a total electricity generation of ≥35% by 2050. Industrialised countries begin to meet this policy target in 2010, while the OOECD region must accomodate present EU-policies (EC, 1997; EC, 2001). The developing regions of ASIA and LAFM start to apply the Renewable portfolio scheme in 2020, according to the targets summarized in Table 15.

Different scenario analyses presented in the literature (UNDP, 2000) estimate the potential long-term contribution of renewable energy sources to the global supplies to be within a range between 20-50% after 2050. The target specified in this study correlates closely with minimum shares of renewables assumed for the 550-ppmv-scenario of DNE21 model (ACROPOLIS, 2003).

Region	Source	Year	2000	2010	2020	2030	2040	2050
		Bound						
NAME	hydro	ACT	2184.0	2228.1	2440.2	2561.4	2666.4	2756.3
		CAP	166.0					
	solar	ACT	0.1	636.2	1162.2	1922.0	2796.0	3572.9
		CAP	0.2					
	wind	ACT	21.1					4437.0
		CAP	2.5					
	biomass	ACT	274.3	491.2	1467.3	2627.7	4705.9	8427.5
		CAP	12.0					
	geothermal	ACT	52.8					973.3
		CAP	3.0					
OOECD	hydro	ACT	2386.4	2509.3	3112.8	3241.1	3337.1	3411.4
		CAP	168.0					
	solar	ACT	0.4	430.7	774.2	1094.8	1563.8	2246.5
		CAP	0.6					
	wind	ACT	82.0					9668.0
		CAP	13.0					
	biomass	ACT	241.5	318.9	571.2	1022.9	1831.8	3280.5
		CAP	14.0					
	geothermal	ACT	44.3					815.6
		CAP	1.8					
EEFSU	hydro	ACT	1035.1	1135.0				5841.0
		CAP	89.0					
	solar	ACT						1580.0
		CAP						
	wind	ACT	0.1					2640.0
		CAP	0.1					
	biomass	ACT	14.5	70.0				10811.9
		CAP	2.0					
	geothermal	ACT	0.3	25.0	50.0			1989.0
		CAP	0.0					
ASIA	hydro	ACT	1455.4	2283.3	4393.5	5447.0	6503.5	7557.0
		CAP	127.5					
	solar	ACT	0.2	1375.1	2062.7	6248.1	10430.3	14618.8
		CAP	0.1					
	wind	ACT	5.4					5880.0
		CAP	1.4					
	biomass	ACT	14.0					53523.0
		CAP	1.9					
	geothermal	ACT	51.4					4978.0
		CAP	2.1					
LAFM	hydro	ACT	2407.2	3450.2	4761.6	6121.3	7412.5	8513.9
		CAP	146.0					
	solar	ACT	0.3	441.9	979.3	1855.2	3331.3	5244.2
		CAP	0.1					
	wind	ACT	1.2					3399.0
		CAP	0.2					
	biomass	ACT	48.3					112384.0
		CAP	3.3					
	geothermal	ACT	29.7	98.0	204.0			2003.0
		CAP	2.1					

Table 14. *Potentials for renewable electricity generation in GMM. Bounds on activity (ACT) are given in PJ/yr; bounds on installed capacity (CAP) are given in GW_{el}.*

The renewable portfolio policy is introduced into the GMM model as follows. The relative share of renewable-energy systems (*ren*) in the regional production of electricity from all technologies (*all*) are constrained to be equal or above a given fraction of total electricity generation. The parameter fr_r represents the regional share of renewables, and *ELE* represents electricity production by region (*r*) and technology. As this constraint is applied at the global level, trade of green certificates is possible (e.g., renewable-deficient regions can "buy" their way into this constraint through the purchase of green-electricity certificates from renewable-rich regions).

$$\sum_{r,ren} ELE_{r,ren} \geq \sum_{r} fr_r \sum_{all} ELE_{r,all} \quad (20)$$

The high market-penetration rate for renewable electricity, as imposed in this study, might go beyond the limits of electricity network stability and its manageability to secure the load profile. In this case, high penetration rates should be followed by renewable sources with back up by fossil-fuel systems. Potential effects of fossil-based back-up systems were not analysed in this exercise. Power-network stability aspects are, however, taken into account by assuming a maximum penetration fraction of intermittent power generation, e.g., wind power and solar photovoltaic, of 25% of total electricity production[5].

Relative share of renewable power generation (%)	2000	2010	2020	2030	2040	2050
OOECD, EEFSU	n.a.	18	23.5	28	31.5	35
NAME	n.a.	15	23.5	28	31.5	35
ASIA, LAFM	n.a.	n.a.	23.5	28	31.5	35

Table 15. *Relative share of renewable electricity production forced by the Renewable portfolio standard scenario.*

A group of four scenarios are designed to analyse impacts of different modalities of a renewable portfolio standard applied over the Baseline scenario (see Chapter 4). The central case in this group of scenarios is the Renewable portfolio scenario, which envisages international policy actions in the direction of trading the green certificates and global learning spillovers. Additional two scenarios presented in Table 16, i.e., Renewable portfolio (no-trade) and Renewable portfolio (no-ETL), have been included in the analysis to contrast the central scenario with the consequences of exclusion of green electricity trade or exclusion of ETL. Finally, the Renewable portfolio (40%) scenario is a sensitivity case that prescribes more stringent renewable-electricity quotas of 40% to be achieved by 2050 for all world regions.

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[5] Issues related to the intermittency of wind power have been analysed in a number of recent studies (e.g., Gül and Stenzel, 2005; DENA, 2005). A conclusion from these analyses can be derived that the integration of a large amount of wind power in the supply mix is technically feasible. However, when wind power contribution to the supply exceeds certain levels (above 10%, depending on the grid structure of the individual country), additional measures on a technical as well as on a regulatory level to avoid potential grid failures may become necessary. Technical measures identified by the above cited studies comprise transmission grid upgrade and extension, enlarged cross-border connections, improvements in forecasting and modelling of natural fluctuations, and installation of more flexible generating capacity, including hydro-power, CHP, NGCC and distributed generation systems. On a regulatory basis, design and regulation of electricity markets and the degree of interconnection between different electricity markets and balancing zones are identified as being critical.

Scenario	*Specification*
Baseline	Baseline case, no renewable policy in 2010-2050, with ETL
Renewable portfolio	Regionalised targets for renewable-electricity share, Partial equilibrium, Trade of green certificates, ETL
Renewable portfolio (no-trade)	Regionalised targets for renewable-electricity share, Partial equilibrium, without trade of green certificates, ETL
Renewable portfolio (no-ETL)	Regionalised targets for renewable-electricity share, Partial equilibrium, Trade of green certificates, no-ETL
Renewable portfolio (40%)	Regionalised targets for renewable-electricity share increased to 40% by 2050, Partial equilibrium, Trade of green certificates, ETL

Table 16. *Naming and description of the Renewable portfolio standard policy scenarios.*

7.1.3. Subsidy scheme

To provide long-term global insights into impacts arising from the implementation of the monetary incentive policies in favour of renewables, a generic subsidy scheme for renewable power generation has been developed. The uniform subsidy levels of 2, 4, and 6 ¢/kWh for each source of the renewable-electricity generation are adopted for the industrialized countries (NAME, OOECD, EEFSU), with this subsidy starting in 2010. The subsidy diminishes linearly to zero in the year 2050. Developing regions (ASIA, LAFM) join the subsidy scheme in 2020 and apply the same subsidy levels as the industrialized regions between the years 2020 and 2050. Similar to the renewable portfolio policies, the global subsidy scheme implies a trade of green certificates across regions. The subsidy levels as a function of time are shown in Table 17.

The hydropower is modeled in an aggregated form in GMM; large and small hydroelectric plants are merged into one generic technology. The subsidy scheme applied herein is intended to distinguish between different scales of hydropower utilization and to provide the support only for the small-scale hydropower. The subsidy for hydropower, therefore, has been limited to a maximum of one third of total hydropower generation; hence, only 33.33% of the total generated hydro-electricity can be subsidized. Similarly, only 1/3 of total hydropower generation is allowed for trading in the form of green certificates.

Subsidy level	2010	2020	2030	2040	2050
	¢/kWh				
I (2¢)	2	1.5	1	0.5	0.0
II (4¢)	4	3	2	1	0.0
III (6¢)	6	4.5	3	1.5	0.0
	$/GJ				
I (2¢)	5.6	4.2	2.8	1.4	0.0
II (4¢)	11.1	8.3	5.6	2.8	0.0
III (6¢)	16.7	12.5	8.3	4.2	0.0

Table 17. *Subsidy levels for renewable electricity generation applied in GMM.*

As mentioned earlier, the subsidies for renewables can be financed by different means. The needed resources can be accumulated through a higher premium payments by electricity consumers, or through taxes imposed on taxpayers and provided to the power utilities. Another option is the fund allocation through an auction, wherein the bidding system allows for competition of renewable projects requiring the lowest incentive; the funding for project implementation is based again on a surcharge on the retail electricity price. Although the way in which the financial resources for subsidies are allocated can be of a vital importance for a successful policy implementation, the specific implementation scheme was not analyzed explicitly in this study. Nevertheless, the total amounts of resources needed for different subsidy levels are briefly discussed in Section 7.2.3.

The generic subsidy scheme, as formulated in this modeling exercise, reduces the generation cost of renewable electricity (*ELE*) produced by technology (*j*) belonging to the group of renewable-energy systems (*ren*). The total quantity (*Q*) of subsidized electricity in region (*r*) per time period (*t*) corresponds to:

$$Q_t = \sum_{j,r} ELE_{j,r,t} \; ; \; j \in ren \tag{21}$$

Subsidized renewable electricity can be simultaneously traded across regions while the net export of green electricity across all regions (*NEX_Q*) is balanced for each time period:

$$\sum_r NEX\_Q_{r,t} = 0.0 \tag{22}$$

The total cumulative discounted energy-system cost (*Z*) is reduced by the cumulative amount of discounted subsidies (*subsidy*) provided over the time horizon:

$$Z_{subsidy} = Z - \sum_t S_t \cdot ypp \cdot Q_t \cdot (1 + dr)^{-t} \tag{23}$$

where S_t is the subsidy rate in a given time period, *ypp* are the years per period (10 years in GMM), and *dr* is the discount rate (5%).

Each of the subsidy levels of 2, 4, and 6 ¢/kWh is modeled in the corresponding scenario, as is summarized in Table 18; modalities with or without trading of green certificates are included. Additional sensitivity model-run has been performed for the 2 ¢/kWh subsidy-level with an extended ETL-option, assuming the endogenous learning rates for biomass and geothermal systems of 5%, and presented herein as the Subsidy-2¢-ETL scenario.

Scenario	Specification
Baseline	Baseline case, no renewable policy in 2010-2050, with ETL
Subsidy-2¢	Subsidy of 2 ¢/kWh provided for renewable electricity production, Partial equilibrium, Trade of green certificates, ETL
Subsidy-2¢ (no-trade)	Subsidy of 2 ¢/kWh provided for renewable electricity production, Partial equilibrium, without trade of green certificates, ETL
Subsidy-2¢-ETL	Subsidy of 2 ¢/kWh provided for renewable electricity production, Partial equilibrium, Trade of green certificates, ETL extended
Subsidy-4¢	Subsidy of 4 ¢/kWh provided for renewable electricity production, Partial equilibrium, Trade of green certificates, ETL
Subsidy-4¢ (no-trade)	Subsidy of 4 ¢/kWh provided for renewable electricity production, Partial equilibrium, without trade of green certificates, ETL
Subsidy-6¢	Subsidy of 6 ¢/kWh provided for renewable electricity production, Partial equilibrium, Trade of green certificates, ETL
Subsidy-6¢ (no-trade)	Subsidy of 6 ¢/kWh provided for renewable electricity production, Partial equilibrium, without trade of green certificates, ETL

Table 18. *Naming and description of the renewable subsidy scheme scenarios.*

7.1.4. Trading of green certificates

The adoption of the Renewable portfolio standard policies implies an optimistic assumption made for the possibility of having a global pool of countries that are willing to participate and trade renewable electricity. Because of technological, natural and economic limitations, the renewable-electricity target can often be achieved in a more efficient way through the introduction of a green certificates trading system. In this case, the green certificates serve as a commodity that represents electricity generated from renewable-energy sources. This commodity is traded (on a regional or local level) between countries/regions with surpluses of generated renewable power and those having limited or expensive possibilities to produce renewable power (Schaeffer et al., 1999).

Since the green certificates are traded among all regions to allocate the investments within the region that offers the most cost-efficient options in producing renewable electricity, the model identifies the same marginal price of green certificates per region for a given time period. As a first approximation, zero transaction costs for implementation of the green-certificate trading system are assumed. This modelling approach can be described as the one that obtains the "where" flexibility of investments in renewable-energy generation technologies. One could also consider a cumulative renewable-energy constraint and obtain an efficient allocation of costs in time and region (so called "when" flexibility), but these scenarios were beyond the scope of the study and, therefore, were not introduced in the present analyses.

For the case of a subsidy scheme complemented with the green certificates trade, subsidies are provided to increase the competitiveness of renewable electricity, which is then traded across regions under conditions where the marginal price of traded green electricity equals the subsidy rate. This “subsidy&trade” approach to setting the policy can help to identify in the long term the most cost-effective method by which subsidies might be spent. Investment in renewable energy projects in world regions with the highest renewable-resource potentials can moderate the cost penalty incurred in reaching the long-term sustainability goals. For both policy tools, i.e., renewable portfolio and subsidy scheme, the trading regime starts in 2010 among industrialized regions and is extended at the global level in 2020.

7.2. Scenario Results

The impacts attendant to the implementation of different modalities of the Renewable portfolio standard and Subsidy schemes are discussed in terms of changes in power generation, primary and final energy demand, and changes in global carbon emissions. The cost impacts reported herein are comprised of changes in total system cost, marginal cost of green certificates, and generation cost for the SPV technology.

7.2.1. Structural changes

7.2.1.1. Electricity generation

The main objective of implementation of the specific policy instruments for promotion of renewable electricity technologies is to increase the competitiveness of these systems as compared to conventional and well-established electricity technologies based primarily on fossil-fuel combustion. As discussed above, penetration of renewable energy in the electricity market is determined by the cost characteristics, exogenously imposed market-penetration rates, and technical potentials assumed (see Section 7.1.1).

Renewable portfolio policies force the share of renewable electricity to achieve market shares specified in Table 15. Electricity generation from fossil-based technologies is steadily reduced over the time period investigated. Both coal- and gas-based generation are affected, and the total contribution of the fossil-energy sources in 2050 is lowered by 25% relative to the Baseline scenario. The role of nuclear energy in the electricity market is also reduced, especially in the last time period. The relative share of hydroelectric and non-hydroelectric renewable power production under the Renewable portfolio scenario increases globally by 86% as compared to the Baseline; in absolute terms the renewable power supply in 2050 rises over the Baseline by almost 10’000 TWh/yr and by 76%.

The obligation for electricity suppliers to deliver 35% of electricity from renewable-energy sources, however, is associated with an increase in cost and a significant attendant reduction in the total power supplied because of decreases in the electricity use on the demand-side of RES (see also Section 7.2.1.5). The reduction in global power generation over Baseline totals to 7% in 2030 and 6% in 2050 for the Renewable portfolio scenario, where trading of green certificates is allowed. As shown in Figure 40, these reductions are even more pronounced when the trading of green electricity is excluded from the policy setup and the renewable electricity quotas can be achieved only by exploitation of domestic renewable resources.

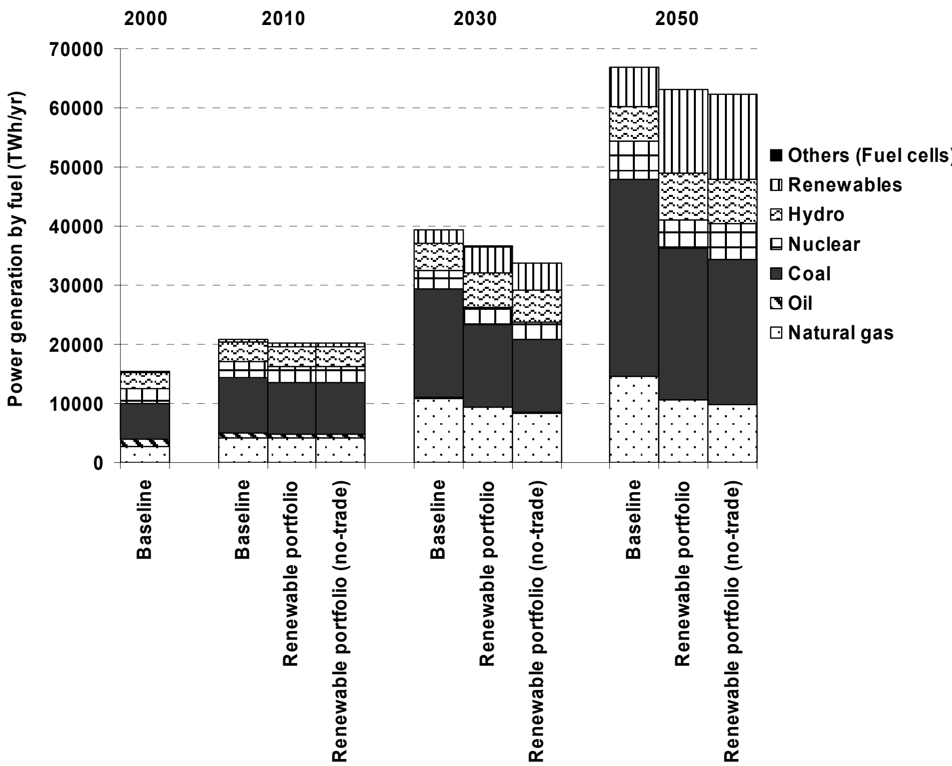

Figure 40. *Development in power generation by fuel under the Baseline and Renewable portfolio scenarios.*

Also, the renewable-energy "subsidy&trade" scheme, as implemented in this study, results in an increased contribution of renewable electricity to the total power generation mix as compared to the Baseline scenario. The feedback in incremental renewables-based generation, as summarised in Figure 41, is most pronounced between periods 2020-2040; however, the growth that peaks in 2030 is reduced towards 2050, as the subsidy level reaches zero.

Electricity generation from renewables on the global level, including hydropower, is increased in the Subsidy-2¢ scenario over the Baseline by 10% in 2030, and by 5% in 2050. For the Subsidy-6¢ scenario the relative increase in power generation by 34% in 2030 and by

14% in 2050 is reported. For the OOECD region, the increases over Baseline scenario conditions in 2030 and 2050 are 13.5% and 4% in the 2 ¢/kWh subsidy level, and 15% and 4.2% in the 6 ¢/kWh case.

The non-sustained impact of subsidies is illustrated further by Figure 53 in Section 7.2.3.1, which shows that the global share of electricity generation from renewables in the Subsidy-2¢ scenario reaches 19.2% in 2030, and remains at the levels below 20% in 2050. With the subsidy level of 6 ¢/kWh, global shares of 23% in 2030 are achieved, but are reduced again to 21% in 2050.

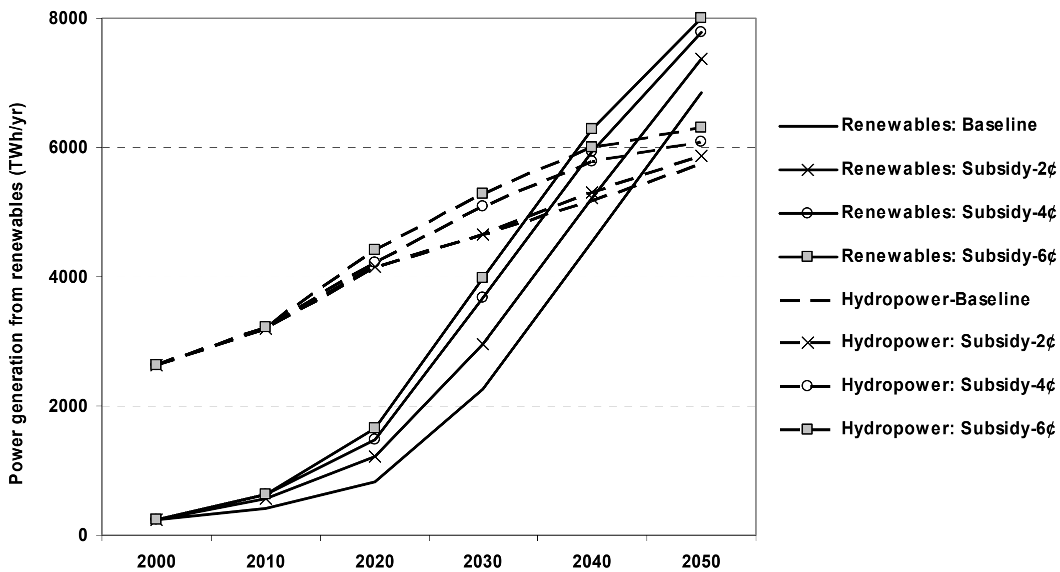

Figure 41. *Power generation from non-hydro renewable sources and hydropower in the Baseline and under the subsidy scheme scenarios.*

Increased generation from renewables induced by the subsidy schemes considered is balanced by the reduced contribution of power production based on natural gas and coal. Figure 42 indicates that lower investments in fossil-fuel fired systems might stimulate a market penetration of nuclear power plants in the end of the time horizon. The relative increase over the Baseline scenario in production from non-hydro renewables is most significant between 2010-2030 (e.g., by a factor of 2 in 2020 under the Subsidy-6¢ scenario) with subsequent decline in later periods; increase in hydropower peaks in 2040.

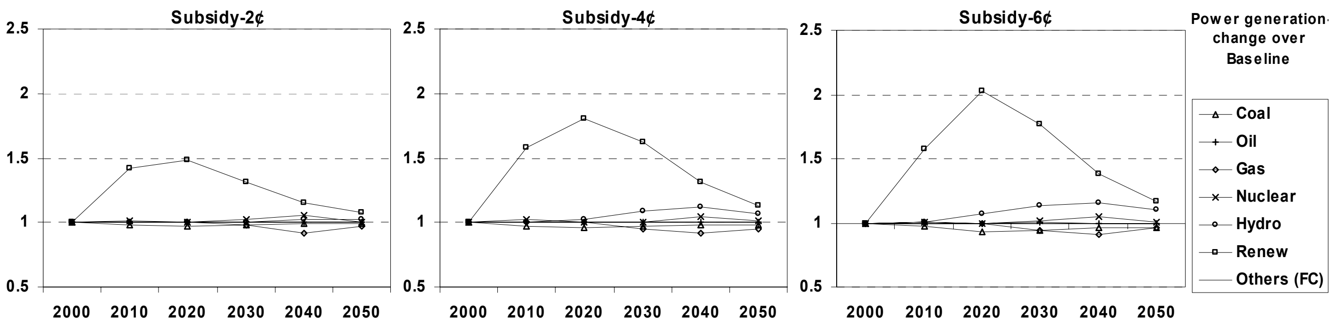

Figure 42. *Change in power generation by fuel relative to the Baseline under different level of subsidy. (Index: Baseline = 1)*

7.2.1.2. Role of renewable technologies under policy scenarios

The profile of electricity generation for the global energy system in 2050 is given in Figure 43 for the Baseline case, Renewable portfolio scenario and scenarios with different subsidy levels. Targets prescribed under the Renewable portfolio standard are achieved by a significant increase in electricity generation from biomass, hydropower, geothermal sources, as well as from SPV systems.

Biomass-fueled power plants experience the most significant increase with respect to the Baseline reference development. On the contrary, growth in generation from wind turbines is not substantial, since this technology is already approaching its assumed technical potential under the Baseline conditions. The Renewable portfolio scenario is the only one where the SPV technology gains a market share in 2050. Increases in renewable electricity generation are balanced by reductions from NGCC, advanced nuclear systems (NNU), and most significantly, from conventional and advanced coal-fired power plants.

The electricity generation mix in 2050 for the renewable subsidy scheme suggests that the electricity supply from hydropower, biomass and geothermal systems increases with a higher subsidy level. Larger contribution from wind power is again bounded by its potential-limits and by the growth rate assumed. Changes in power generation from systems based on combustion of fossil-fuels are determined by the structural shifts in previous periods and occur at a lower extend than in the Renewable portfolio. Total generation from fossil fuels, however, is reduced by the end of the computational period.

Figure 44 illustrates how the different renewable technologies contribute to the fulfilment of the Renewable portfolio obligation in 2030 and 2050 under different policy modalities. While market-penetration levels for renewable-energy systems differ only little in 2030, notable changes are reported for the end of the time horizon. In the scenarios with ETL-option active, i.e., Renewable portfolio and Renewable portfolio (no-trade), the 'learning' technologies (wind turbine and SPV) achieve a higher penetration rate with respect to the scenario that does not consider technological learning. On the contrary, the Renewable portfolio (no-ETL) scenario projects a slightly larger production from biomass power stations.

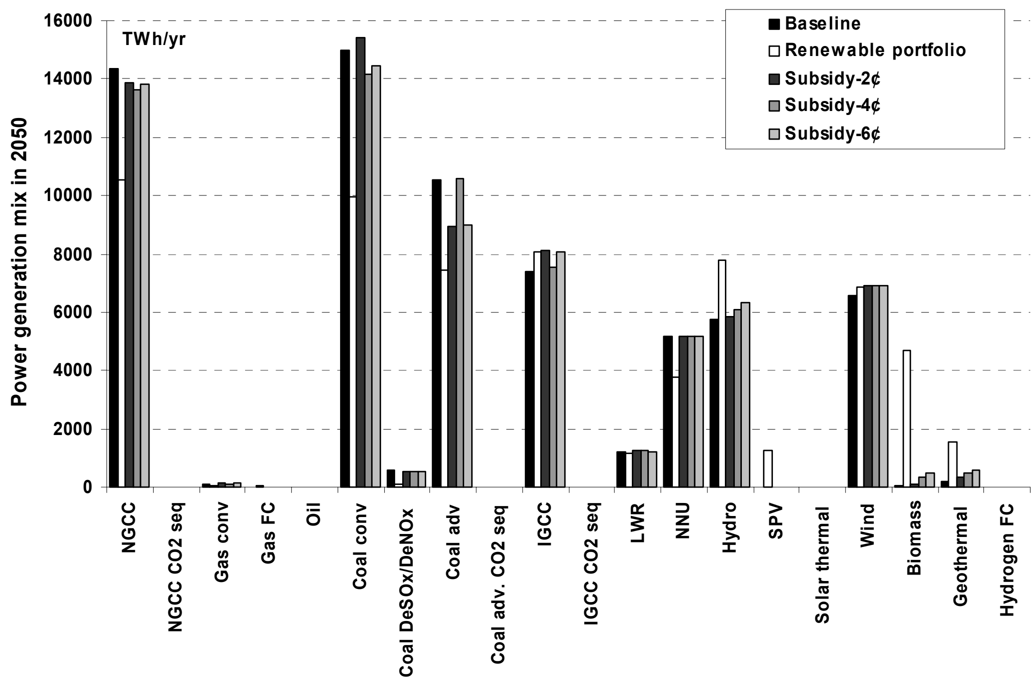

Figure 43. *Contribution of technologies to the global electricity generation mix in 2050 in renewable-policy scenarios. For nomenclature, see Table 8.*

Another interesting observation is made for penetration of SPV systems when comparing policy options with and without the trading of green certificates. In the case that allows for the green certificate trade, the SPV systems contribute by 50% less than in the case without trade. This reduced SPV contribution is explained by an improved access to the cheaper technological options, in particular biomass, hydroelectric and geothermal power, which is facilitated by the trading regime in the Renewable portfolio case with trade. Both modalities of the Renewable portfolio standard can have essential impacts on the cost-effectiveness of the policy implementation, as is discussed further in Section 7.2.3.

The subsidy scheme for renewable power production induces lesser impact on the renewable technology penetration as compared to the Renewable portfolio policies. Since the wind turbines increase substantially the contribution to the power generation mix already in the Baseline, further increased production from this technology is limited by the upper bounds imposed on this technology. On the other hand, biomass and geothermal sources experience more significant increase over the Baseline scenario.

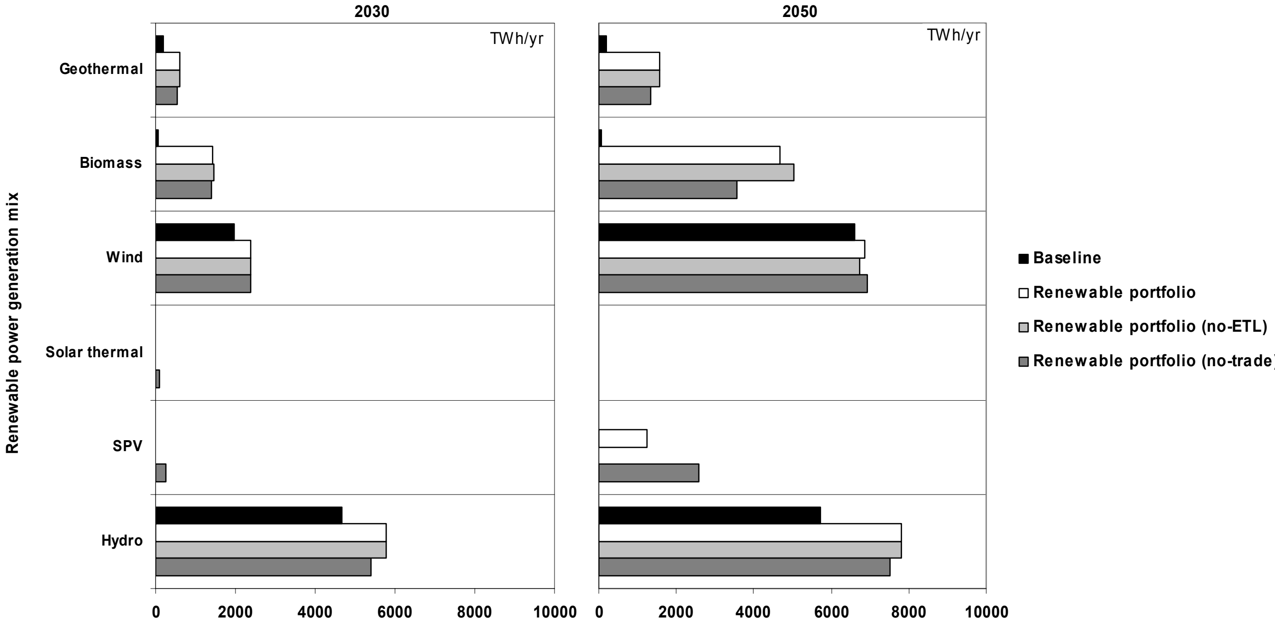

Figure 44. *Penetration of renewable-electricity generation technologies in 2030 and 2050 under selected modalities of the Renewable portfolio scenario.*

As is shown in Figure 45, an increase in generation from biomass peaks around 2030 in the Subsidy-4¢ and Subsidy-6¢ scenarios, while the geothermal plants contribute the most in the period 2040 in all cases considered. Power generation from biomass and geothermal plants is lowered significantly in 2050, where the subsidy is not provided. A similar trend, depicted separately in Figure 41, is reported for hydropower. No impact is observed for the penetration of SPVs in the Subsidy-2¢ and Subsidy-4¢ scenarios. Only the 6 ¢/kWh subsidy-level results in a subtle market expansion, which is further enforced by the ETL performance of SPVs.

If the 'learning-by-doing' option is applied for biomass and geothermal power plants in the sensitivity scenario Subsidy-2¢-ETL, significant increase in power production from both systems occurs over the whole time horizon as compared to the Subsidy-2¢ case. Decrease in investment cost due to the installed-capacity doublings, together with the subsidy supplied into these technologies, results in a substantial production increase, especially in regions of EEFSU, ASIA and LAFM. Subsequently, the growth in total contribution from renewable systems continues beyond the period 2040, as opposite to the scenario with ETL applied only to the wind and SPV systems. Renewable electricity production increases over the Baseline by 38% and 41% on the global level in 2030 and 2050.

The relative share of renewable electricity in the total power production increases to 26% in 2050, as compared to less than 20% share achieved in the Subsidy-2¢ scenario without ETL-option active for biomass and geothermal plants (see also Figure 53). This result suggests that early learning investments in biomass-fuelled power generation technologies in regions with the large biomass-resources potential can accelerate introduction of renewable electricity technologies into the market.

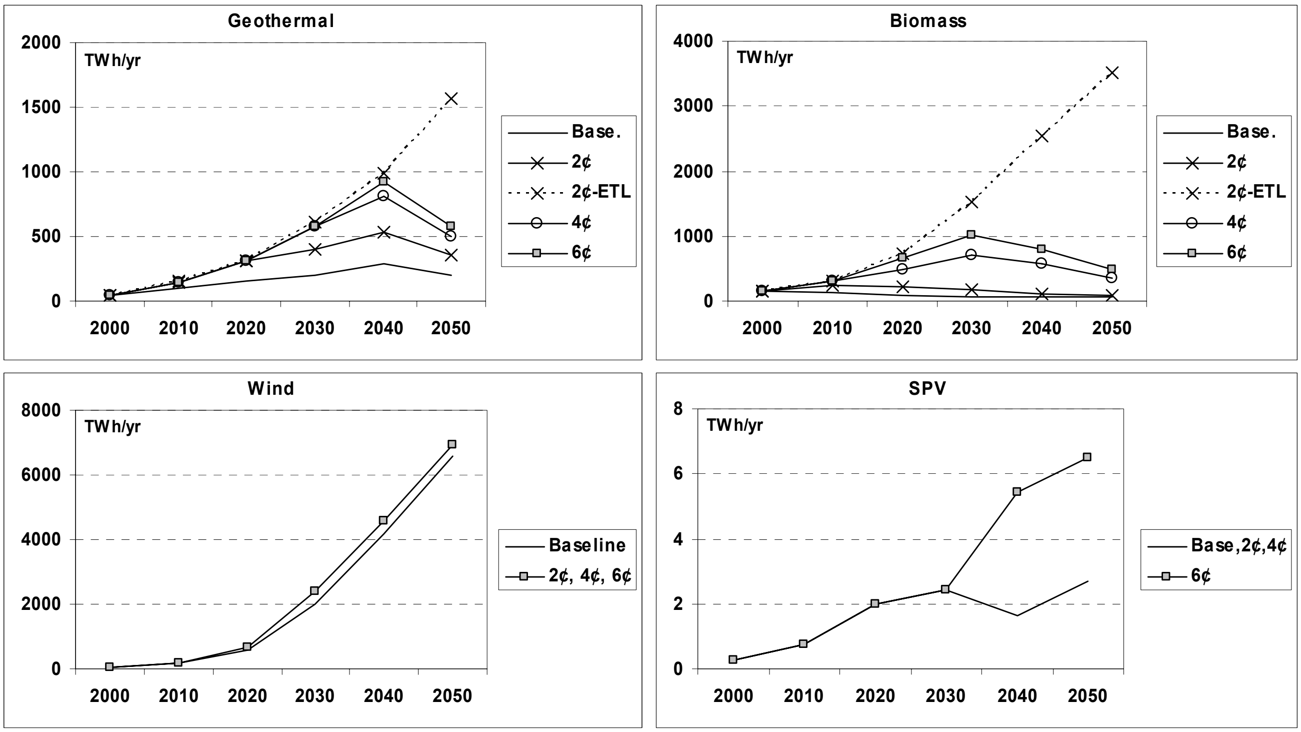

Figure 45. *Power generation from non-hydro renewable electricity technologies under different level of subsidies.*

Figure 46 illustrates the regional distribution of the additional renewable electricity generation for the scenario with 2 ¢/kWh subsidy level and for the sensitivity scenario (Subsidy-2¢-ETL) with endogenous learning applied to all renewable electricity sources except hydro-power. In the former case, the largest increment in renewable power production is observed for regions NAME and OOECD during the period 2010-2030, with biomass, wind turbines and geothermal plants being the fastest growing systems. The OOECD region holds the largest fraction in the additional generation in 2030 because of the increase in contribution from wind power and partly from geothermal plants. Increases in hydroelectric and wind power make the LAFM region the main contributor to the incremental renewable-energy production by the end of the computational period.

In the Susbsidy-2¢-ETL case the additional renewable-electricity generation is distributed almost equally across the regions in 2030. The contribution from EEFSU, ASIA and LAFM regions, however, prevails in 2050 as a result of significant penetration of biomass-fuelled systems.

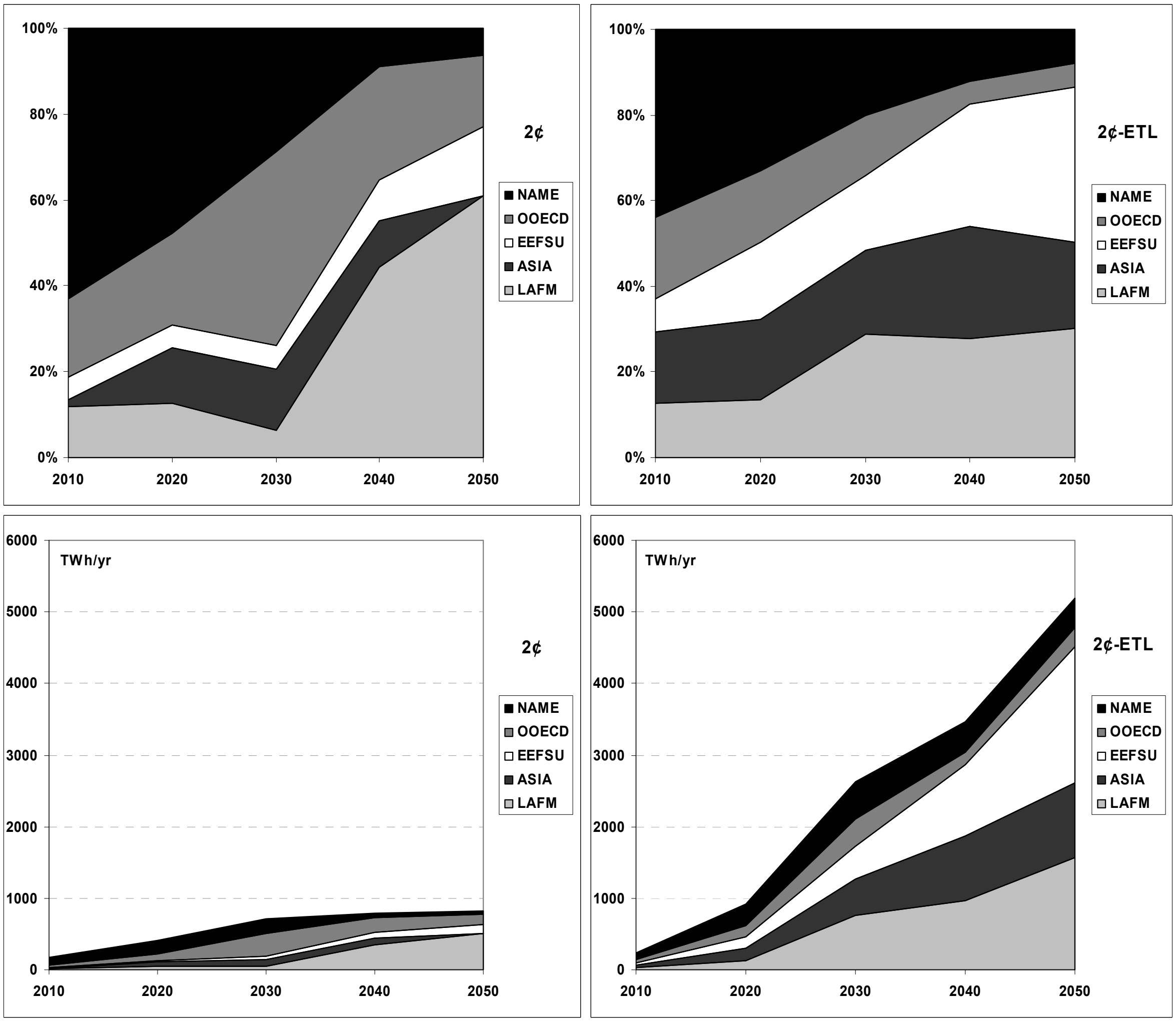

Figure 46. *Regional distribution of the additional renewable electricity generation under 2 ¢/kWh subsidy level.*

7.2.1.3. Inter-regional trading of green certificates

As discussed in Section 7.1.4, international trading of green certificates across world regions can help in identifying the most efficient locations to install renewable electricity systems and at the same time moderates the policy-induced cost impacts. Marginal cost of green certificates globally traded, and the impacts of the trading regime on the total energy system cost, are provided in Section 7.2.3.1.

Figure 47 depicts the time evolution of the green certificates trade across regions participating to the trade-regime under both the Renewable portfolio and Subsidy-2¢ scenarios. In the former case, the dominant exporters of green certificates are the ASIA and LAFM regions.

The industrialized regions, i.e., OOECD, NAME and EEFSU, import the green certificates throughout the time-frame analysed. The amount of green electricity globally transferred among regions steadily increases from about 900 TWh in 2020 to 2400 TWh in 2050 (14% and 11% of global generation from renewables, respectively). The total quantity of green certificates purchased by a given region is determined by the allocation of targets of the renewable portfolio standard, by the ability of regional RES to fulfil the renewable obligation through exploitation of domestic resources, and, finally, by the availability of cheaper options in exporting regions.

The development of the green certificates trading for the Subsidy-2¢ scenario shows notably more fluctuations in periods 2010-2050 and requires a careful interpretation. For example, the OOECD region oscillates between a buyer and a seller position over the given time frame. The main suppliers of green electricity are the LAFM and ASIA regions, while the NAME and EEFSU regions remain certificate buyers until the end of computational period. It has to be emphasised that the subsidy-scheme policies do not impose any renewable-electricity constraint over the energy system. The driving forces behind the green electricity trade, therefore, are different than those in the Renewable portfolio scenario. First, when the renewable electricity is subsidized and traded, the model finds the optimal locations where the subsidy is used. Furthermore, the purchase of renewable electricity allowed in this specification can contribute to the satisfaction of the end-use electricity demands that drive the GMM model. Based on the observations made here, it is questionable whether this "subsidy&trade" regime is a realistic option in the long run; however, such a regime provides a platform for illustrating possible combination of the domestic incentives and international policy instruments.

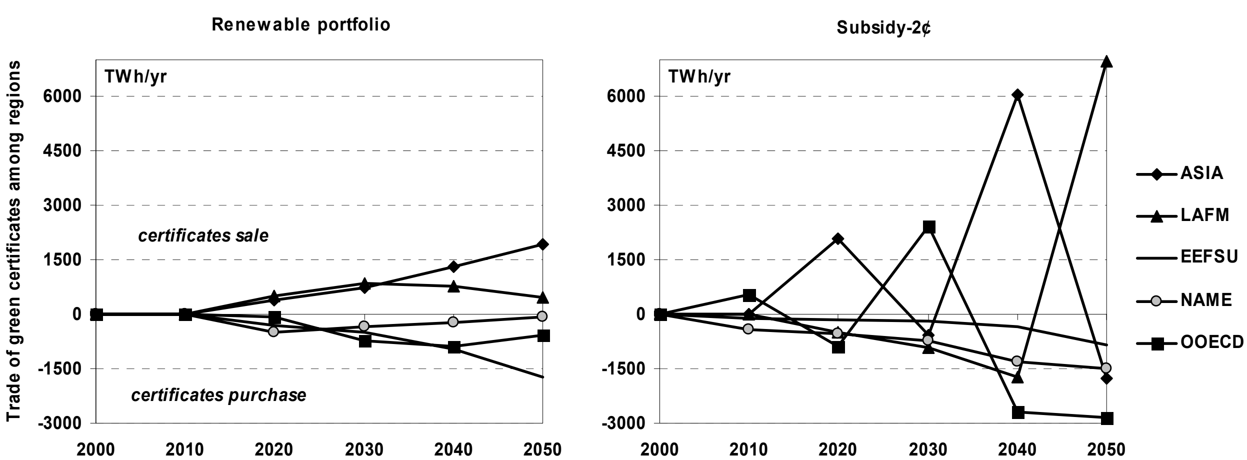

Figure 47. *Trade of green certificates for the Renewable portfolio and the Subsidy-2¢ scenarios.*

7.2.1.4. Primary energy consumption

Change in primary energy demand, as compared to the reference development, follows basically the development in the electricity sector for both renewable policy instruments under examination. In the case of the Renewable portfolio standard imposed on the Baseline, the contribution of hydro and non-hydro renewables reaches more than 25% of the global primary energy consumption in 2050. As is illustrated by Figure 48, increases in consumption of the non-hydroelectric renewable resources are significantly higher as those reported for hydropower. The global potential for hydropower utilization provided in Table 14 is fully exploited by 2050 under the Renewable portfolio scenario. The main contributor to the growth of non-hydro primary supplies at the end of the computational period is biomass, followed by the geothermal and solar energy, with the technical potential exploitation rates of 52% and 16%, respectively. The potential for wind energy is utilised by 50% despite the limitations imposed on the speed of market penetration.

Renewables substitute for other fuels, particularly for coal and nuclear energy, where reductions by 20% and 23% relative to the Baseline scenario are observed in 2050. Reductions for natural gas and oil demand are reported only in decades around 2040 and 2050, whereas the increases in periods 2020-2030 are attributed to the higher use of these fuels in the end-use sectors in order to substitute for more costly electricity (see Section 7.2.1.5). The overall reduction of primary energy use with respect to the Baseline scenario is about 1% in 2050.

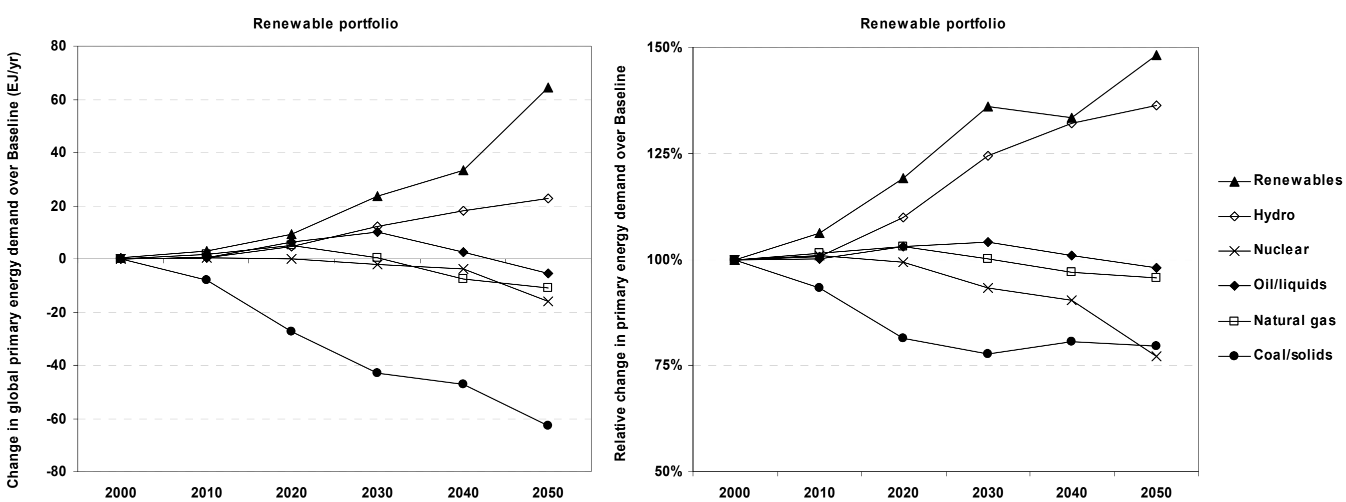

Figure 48. *Change in global primary-energy use for the Renewable portfolio scenario by fuel relative to the Baseline (Index: Baseline = 100%).*

Figure 49 compares the impact of subsidy level on primary-energy fuels consumption. While the demand for renewable-energy sources and hydropower increases with increasing subsidy level by 2040, consumption of coal, natural gas and oil is reduced relative to the reference development. Around 2040, nuclear power contributes by a slightly higher level to the total primary demand relative to the Baseline scenario. In general, changes in primary energy consumption over Baseline conditions under the renewable-energy subsidy scheme are less pronounced as compared to the Renewable portfolio scenario, and the contribution of renewable energy sources tend to decrease once the renewable-energy technologies are no longer subsidized in 2050.

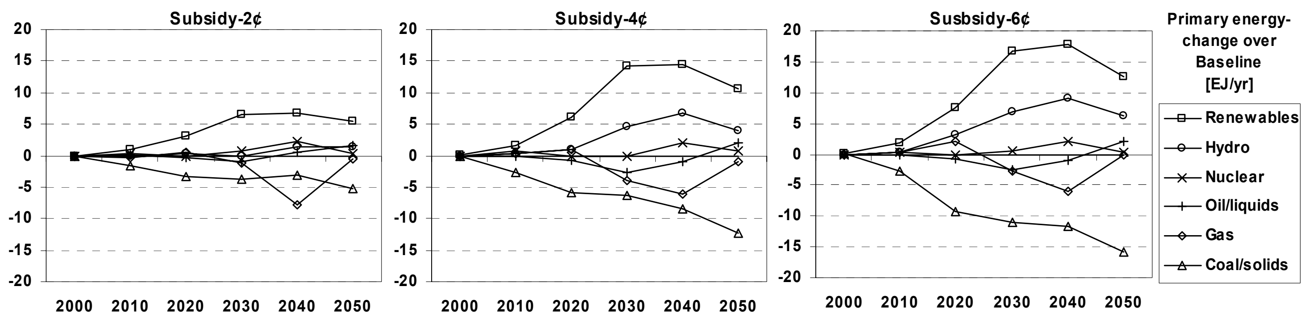

Figure 49. *Change in the primary energy consumption over the Baseline for different subsidy levels.*

7.2.1.5. Final energy demand

As discussed in Section 7.2.1.1, policies that adopt the renewable portfolio obligation within the reference energy system (RES) invoke a decrease in the overall power generation, since the production cost of electricity increases. The induced increase in electricity prices results in electricity demand reductions and substitution of electricity for other fuels by the end-users. As shown in Figure 50, the largest decrease in electricity consumption in the Renewable portfolio scenario is observed around 2040 and accounts for -8% relative to the Baseline levels. Electricity demand reduction in a given period is one of the indicators of the severity of the renewable policy targets being applied. The reduction in electricity use is balanced by a growing demand for natural gas and oil.

A different behaviour of the demand side of RES is observed for scenarios assuming financial incentives provided to renewable electricity production. By 2030, a significant rise in electricity consumption is reported under the subsidy schemes on the global level. The growth in electricity demand is reduced with diminishing subsidy payments in 2040 and 2050. Under the subsidy scheme, the most affected uses of fossil fuels are those for oil and natural gas, with relative demand reduction over the Baseline around 2% in 2030. The contribution of biomass and other fuels is slightly reduced as well. The highest increase in electricity consumption is reported for the Subsidy-6¢ scenario in the industry sector, which benefits the most from subsidies applied to the renewable power generation and shows the greatest ability to replace fossil fuels with electricity.

The policy instruments considered in this study are applied only to the renewable energy systems in the electricity sector. An alternative policy formulation could be implemented that enhances the scope of renewables stimulation to other sectors, i.e., heating and transportation sectors. For instance, a subsidy for solar-thermal collectors or for the production of alternative transportation fuels based on biomass might result in a stronger fuel-switching effect, and to a higher share of renewables in primary and final energy consumption.

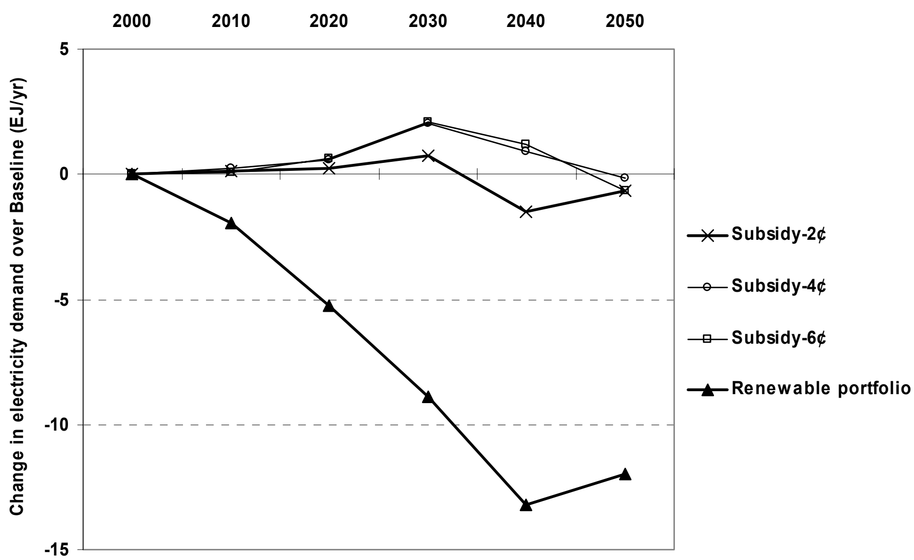

Figure 50. *Change in global electricity consumption over the Baseline for the Renewable portfolio and for different subsidy level.*

7.2.2. Environmental impacts

Global CO_2 emissions

The increased role of renewable electricity sources in the primary-energy mix induced by the Renewable portfolio standard and subsidy scheme is reflected in carbon emission reductions as compared to the reference scenario. Figure 51 indicates that energy-related CO_2 emissions in the Renewable portfolio scenario are continuously reduced over the time horizon with respect to the Baseline, and the total decrease of more than 10% is reported by 2050. The annual reduction of 1.7 GtC/yr in 2050 is primarily associated with the 35%-share of the zero-carbon renewable-energy technologies in the generation mix, as well as being associated with the invoked reductions in coal and natural gas use for electricity production. Additionally, the overall primary-energy demand reduction contributes to the decrease in carbon emissions.

In the case of the subsidy scheme, the highest reduction in CO_2-emissions emerges in 2030 and continues at a lower pace towards the end of horizon. Cumulative carbon-emission reductions for the Subsidy-2¢ scenario between 2010-2050 over the Baseline scenario represent nearly 20 GtC, while this reduction is almost three times higher in the 6 ¢/kWh subsidy level.

The CO_2-reduction trajectory in the Subsidy-2¢-ETL sensitivity scenario shows a declining trend that is sustained over the modelled computational time, despite the subsidy-elimination in 2050. The continuous emission reduction is a consequence of the substantially larger introduction of biomass and geothermal electricity induced by the cost-reducing effects of ETL in the Subsidy-2¢-ETL scenario as compared to the case where endogenous learning for biomass and geothermal plants is not considered.

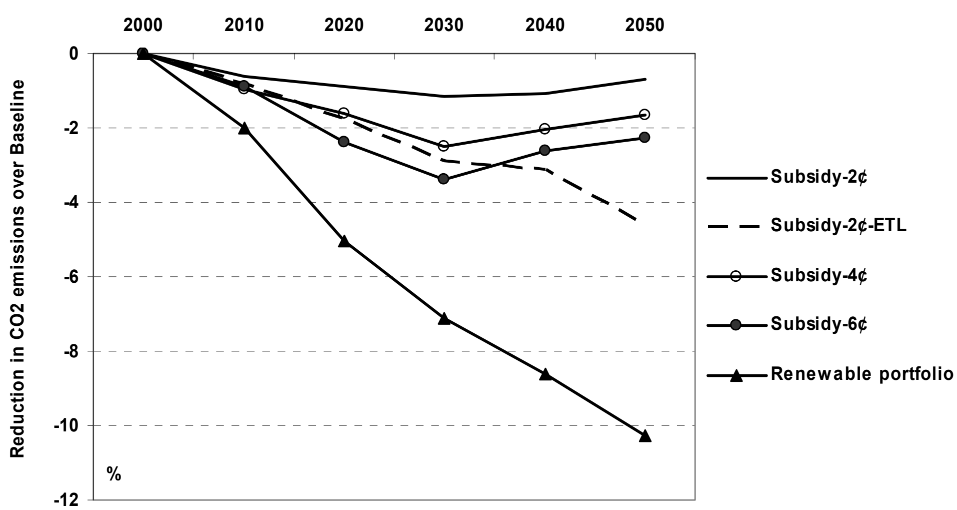

Figure 51. *Change in CO_2 emissions in the renewable policy scenarios relative to the Baseline.*

7.2.3. Cost impacts

7.2.3.1. Green certificates price

Analysis of the marginal price of green certificates indicates the cost-effectiveness of policy instruments for promotion of renewables under investigation conditionas adopted in this study. As summarized in Figure 52 and Figure 53, different shares of renewable power generation can be achieved at different cost levels, depending on the policy setup.

The marginal price of green certificates in the Renewable portfolio scenario is equal to the marginal cost (or the shadow price) of the globally traded renewable-electricity constraint defined by the regionalized production quotas, as is discussed in Section 7.1.2. The marginal cost varies in the case of Renewable portfolio policy-adoption over the time horizon within a range from 2.6 ¢/kWh to 5.2 ¢/kWh. More important than numerical values is that the increased amount of green certificates available for trade in 2020 (from this period onward the regions with large renewable-energy potentials - ASIA and LAFM - start to implement the policy target) results in price reduction in years 2020-2030, as compared to 2010.

If the renewable fractional target indicated in Table 15 has to be reached under the policy framework not allowing for the learning-investments in the selected renewable technologies, as is the case for the Renewable portfolio (no-ETL) scenario, the price of green certificates increases by up to 35% in 2050. This increase is even higher when compared to the sensitivity case Renewable portfolio (40%), which forces a more stringent renewable-electricity obligation of 40% to be fulfilled by 2050.

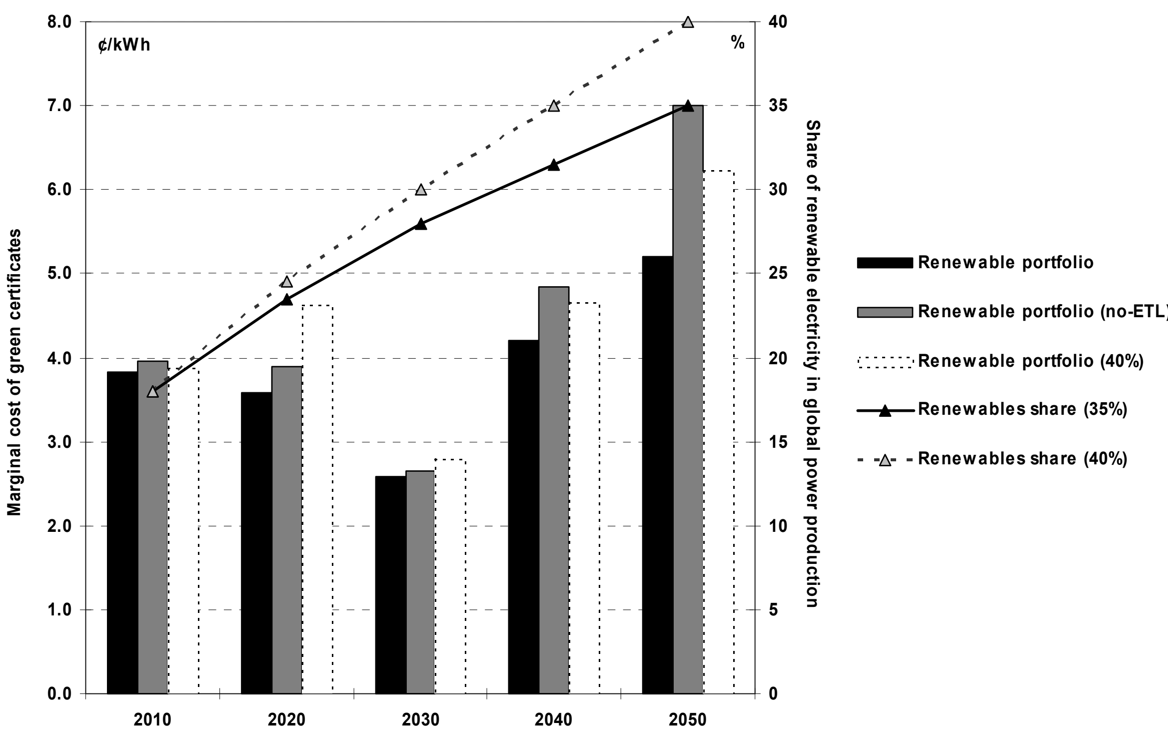

Figure 52. *Marginal cost of green certificates and the relative share of renewables in the total power generation under the Renewable portfolio policies.*

The subsidy scheme, as implemented in this study, implies a cross-regional trading of “green certificates” among the world regions; the level of subsidy, therefore, equals the marginal cost of renewable electricity traded between 2020 and 2050. Under the subsidy scheme the incentive is provided equally to each renewable source (with an exception for hydropower), whereas under the Renewable portfolio constraint the model finds the least-cost solution that defines the supply curve of renewables.

When comparing the effectiveness of both policy instruments in terms of marginal cost and achievable renewable-electricity shares, the Renewable portfolio reaches a higher penetration of renewables at the cost levels that are initially lower than the most generous 6 ¢/kWh subsidy scheme. Furthermore, the modelling results provided in Figure 53 indicate that the 'flat-rate' subsidy scheme that assumes the elimination of subsidies in the long-run might not be able to assure the continuous growth in the renewable-energy market share.

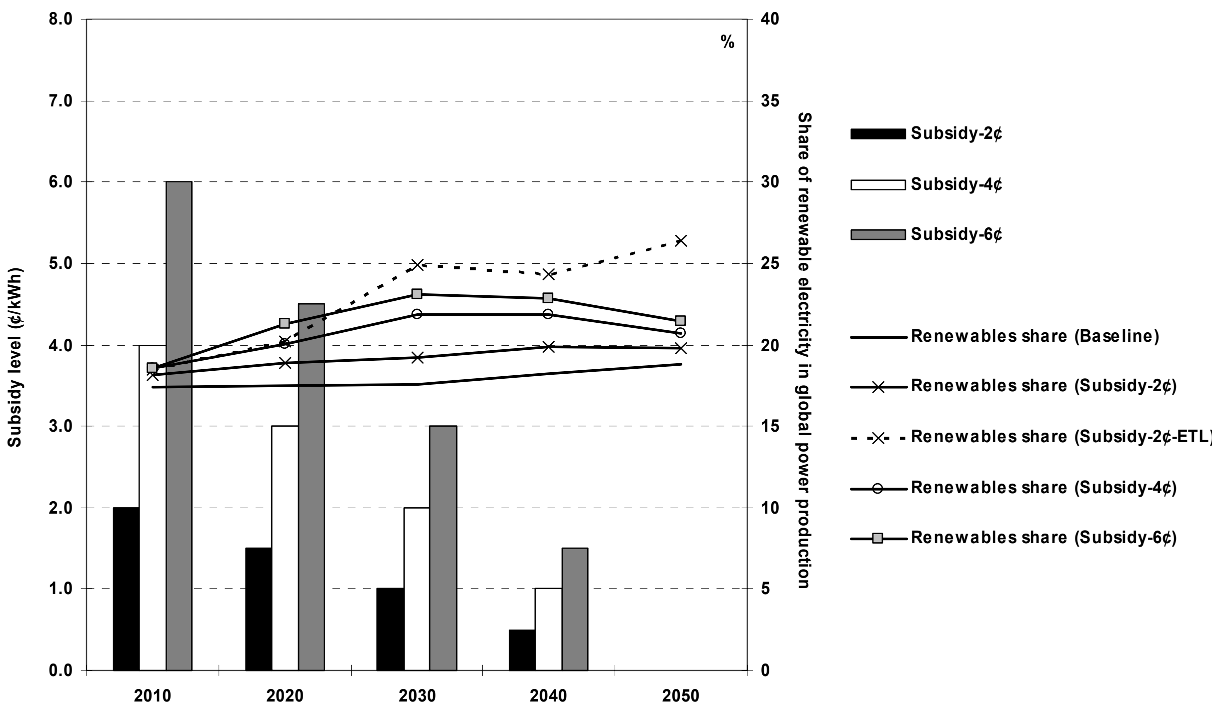

Figure 53. *Marginal cost of green certificates and the relative share of renewables in the total power generation under different level of subsidy.*

It should be noted that the analysis of marginal price of green certificates as provided in this section is not fully comprehensive, since additional costs arising from the implementation of the policy instrument, e.g., verification, monitoring and registration of green certificates, were not considered. Transaction costs, however, might influence the successful implementation of any of the trading regime proposed.

7.2.3.2. *Electricity generation cost analysis (example of SPV)*

An example of SPV market penetration is provided here to document the level of support needed for new technologies that cannot compete under present market conditions against well-established generation systems. As is shown in Figure 45, the market penetration of SPV under the 6 ¢/kWh subsidy-level increases over the Baseline or the Subsidy-2¢ case. Electricity generation from SPV in the Subsidy-6¢ counts for 6.5 TWh/yr in 2050 and corresponds to 0.01% of the annual electricity production. The cumulative investment needed for this level of penetration is nearly 20 billion $\$_{2000}$. However, the generating cost for SPV remains at levels much higher than the cost for competing conventional power plants, which varies between 3.3 to 6 ¢/kWh.

Under the Renewable portfolio scenario, SPV systems penetrate the electricity market in periods 2040 and 2050 at the cumulative production levels of 15'000 TWh worldwide. This significant increase in generation from SPV technologies and the associated increase in cumulative installed capacity implies the reduction in specific investment cost from an initial value of 5000$/kW to 1000$/kW in the year 2040. As shown in Figure 54, the generating cost for SPV systems undergoes a strong reduction due to the 'learning-by-doing' effects and around 2040 reaches a level of 5 ¢/kWh, which can be considered as a break-even point for SPV technology.

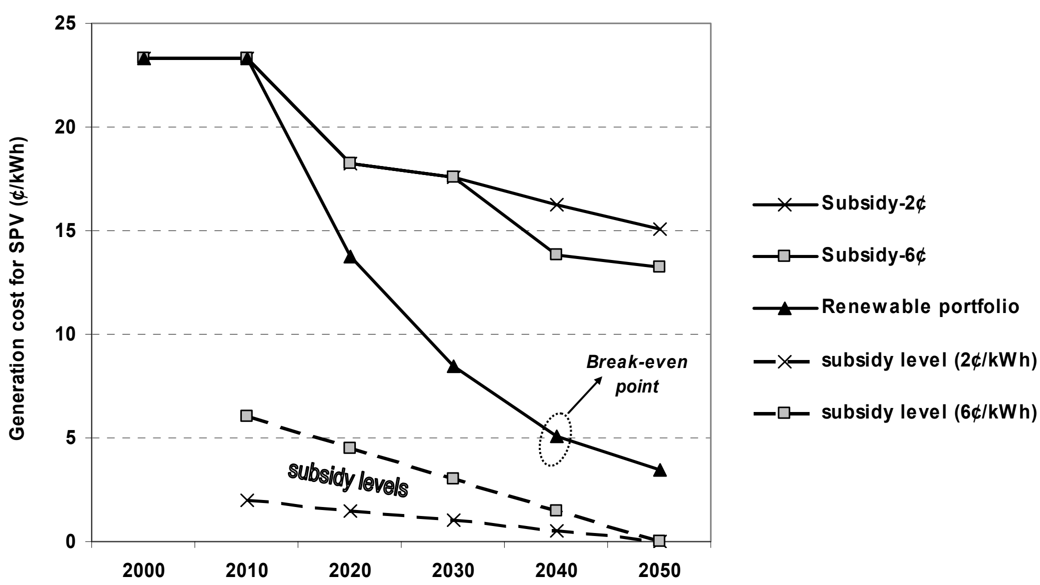

Figure 54. *Generating cost for SPV and the subsidy level for 2¢ and 6¢ cases. Assumed learning rate for SPV is 19% meaning that each doubling of cumulative capacity reduces the specific investment cost by 19%.*

The cumulative undiscounted investment cost, or the global learning-investments necessary to reach the breakeven point of SPV systems in the Renewable portfolio scenario, by 2040, is quantified to around 280 billion $\$_{2000}$. Gaining this immense amount of learning investment will be a challenging task, although a proper application of promising policy options, e.g., feed-in tariffs, tax credits or a stimulation of niche markets, may contribute to the overall cost reduction. It has to be recognised this illustrative example only attempts to identify the order of magnitude of the future investments needed for SPVs to progress down the learning curve.

In addition, Figure 54 also indicates that application of flat subsidies may result in a situation, where mature technologies (for example wind power) receive subsidies, while technologies like SPV remain under-subsidized.

7.2.3.3. Total system cost

Implementation of the renewable portfolio standard forcing a 35% share of renewable electricity production by 2050 combined with the flexible international policies of green certificates trading is accompanied with 1.2% increase in total system cost relative to that of the Baseline scenario.

The Renewable portfolio modalities that disregard the possibilities either to trade green certificates or to benefit from technological learning increase the total cost-penalty induced by the policy adoption by around 75%. This increase is explained by the restricted access to the cheaper renewable resources in developing countries for regions with limited renewable potentials. In this case, the obligation to generate the prescribed portion of renewable electricity is fulfilled by exploitation of more costly domestic resources, which requires investments in capital intensive technologies, e.g., SPVs. As shown in Figure 55, increases in total system cost due to elimination of the green certificates trading and ETL are actually by 35% higher than in the Renewable portfolio policy formulation asking for 40% contribution of renewables by 2050.

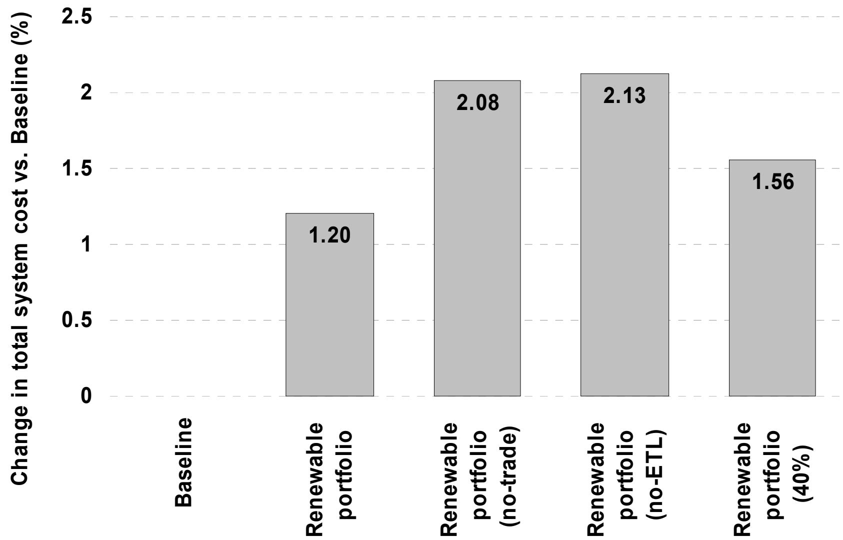

Figure 55. *Change in the total discounted system cost relative to the Baseline for different modalities of the Renewable portfolio scenario.*

The modeling results suggest insignificant changes in the total discounted system costs for the renewable subsidy schemes considered herein as compared to the Baseline scenario. The change in total system cost over Baseline conditions illustrated as positive values in Figure 56, however, represents only the sum of system cost associated with technology switching, new-capacity investments, and fuel substitution.

In all scenarios this total cost increase is below 0.5%. Nevertheless, the total amount of subsidies (negative values in the same figure) globally required for renewables to advance in the rate of market penetration is substantive. Cumulative undiscounted subsidies expended in the Subsidy-6¢ scenario total for almost 5000 billion $\$_{2000}$[6], but the flat subsidy-rate for all technologies does not emerge in a significant penetration of expensive technologies, e.g., solar PV systems. Finally, the modeling results for the subsidy scheme policy-scenarios, assuming the trade of green electricity, suggest that the total cost are reduced by 50% as compared to the cases where the trading is not implemented.

[6] The total cumulative subsidies provided between 2010-2040 under the Subsidy-6¢ scenario amounts to about 0.2% of the cumulative global GDP projected for that period by the SRES-B2 scenario (see Section 4).

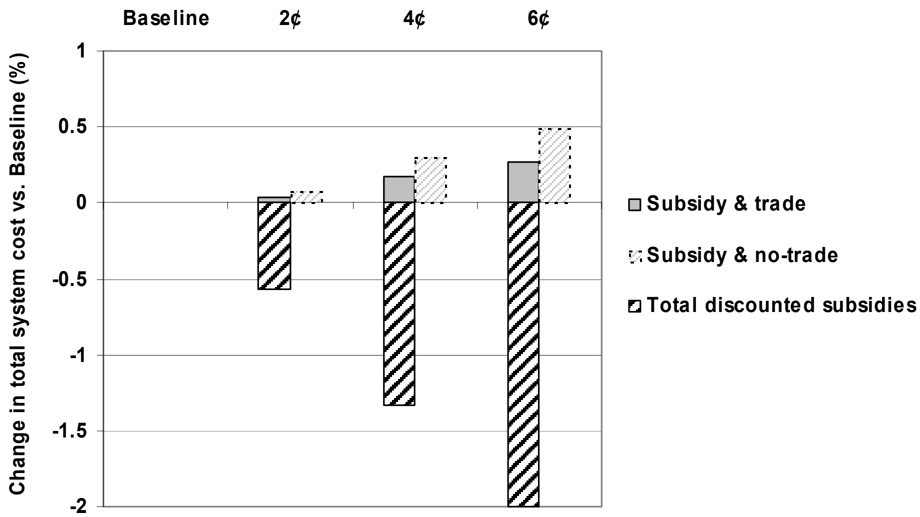

Figure 56. *Change in the total discounted system cost under different level of subsidy relative to the Baseline distinguishing the amount of subsidies provided for renewable electricity production.*

7.3. Summary and concluding remarks

The focus of this chapter has been placed on policy instruments that stimulate the use of renewable energy resources in the electricity sector in the long term. The analysis is extended to the global energy system that envisages a world-wide effort to promote the renewable energy use as an essential aspect of introduction of renewables at a sizeable market levels. Additionally, the global focus is important because of regional differences in distribution of renewable energy potentials, which implies a need to search for cost-effective ways to achieve sustainability goals attendant to the increased utilization of renewable sources.

Two policy instruments under investigation, i.e., the renewable portfolio standard and a generic subsidy scheme, both accompanied with the international green certificates trading regime, have proven feasible and led to a considerable market penetration of the power generation technologies based on renewable energy sources. A number of policy modalities and set-ups that refer to international cooperation and technological learning, however, influence the modelling outcomes, as summarized below.

The Renewable portfolio standard, as implemented in this study, represents a 'cap-and-trade' policy that forces the electricity generation from renewable-energy sources to reach a global level of 35% by 2050. The associated increase in the total cost is computed to be 1.2% relative to the Baseline development. The most significant increase in power generation from renewable-energy sources over the Baseline is reported for biomass technologies, geothermal plants, and hydroelectric power. Wind power is highly competitive already in the Baseline scenario, and the policy-adoption does not influence substantially the market penetration of this technology. At the end of the time horizon, SPV systems are introduced into the power generation mix at a considerable level (market share of 2% in 2050).

An important observation emerging from this study is that market-oriented policies that favour the trading of green certificates across all world regions identify the most efficient locations to install renewable-energy systems and thereby moderates the induced cost impacts. The price of green certificates resulting from the constraint applied is competitive when compared to the present costs for electricity generation. However, potential expenses associated with the implementation of the trading regime (i.e., the transaction cost) have to be considered and quantitatively assessed. Another prerequisite to successful implementation of this policy instrument is the need to convince market actors to invest in renewable-energy technologies for the initial period of their market penetration, when the new systems are not competitive.

In the case of subsidy scheme, the level of penetration of renewables within the electricity market increases with increased levels of subsidy provided. Nevertheless, for a lasting long-term growth of shares of renewable power generation, the elimination of the subsidies by 2050 is probably not adequate and may lead to a situation, where promising new technologies, e.g., SPV, remain locked-out. For example, the highest relative increase by 34% in the penetration of renewable electricity-supply technologies over the Baseline is reported for the 6 ¢/kWh subsidy level in the year 2030, but is reduced afterwards when the subsidy is eliminated. This finding indicates that instead of applying a flat subsidy rate, a more complex subsidy scheme that takes into consideration actual competitiveness of a given technology to avoid potential over- and under-subsidizing is is appropriate. On the other hand, extension of the 'learning-by-doing' option for the biomass and geothermal plants results in a significant increase in the power production from renewables that is sustained over the whole computational period. But again, implicit to this development are early investments in systems based on e.g., biomass, in regions with large biomass-fuel potentials.

The increased utilization of renewable energy sources exhibits various impacts on the sustainability performance of the global energy system. First, the reliance on carbon-intensive fossil fuel supplies (mainly coal and natural gas) is reduced significantly under both policy instruments in favour of renewables in comparison with the reference development. Reductions in oil use are less pronounced, since the policy tools applied are targeted primarily at the electricity sector. An alternative policy setup that extends the scope of renewables stimulation to other sectors, namely to the heating and transportation sectors, might lead to even higher share of renewables in primary and final energy consumption. With respect to the comprehensive analysis of the role of renewables in sustainable energy futures, it is important to stress that the estimations of potentials and market growth-rates for renewable electricity systems are particularly important, since they determine the modelling results for both the Baseline and policy scenarios.

Enhanced introduction of renewable electricity sources in the primary energy mix emerges in a decarbonisation effect, which is pronounced the most in the Renewable portfolio scenario with the total decrease over the Baseline of more than 10% in 2050. The decrease in CO_2-emissions is primarily associated with the substitution of coal and natural gas use in the power sector with the zero-carbon technologies based on renewable resources. The carbon-emission reductions for the subsidy scheme show a peaking behaviour; the highest reduction in CO_2-emissions emerges in 2030 and continues at a lower pace towards the end of horizon.

Market uptake of renewable energy technologies can benefit from both policy strategies adopted in this study, i.e., regulatory measures and economic incentives. Policy insights presented herein suggest that a combination of different approaches will have to be implemented to ensure the lasting impact of renewable systems deployment, which will sustain beyond the periods of the initial policy support. The portfolio of policy instruments might consist of region-specific renewable-energy obligations, technology tailored feed-in tariffs, new capacity or production tax credits, incentives for an exploitation of niche markets, as well as tradable green certificates.

Accumulation of substantial financial resources devoted to learning investments and RD&D expenditures that help to advance the renewable-energy systems along their learning curves is a challenging policy task. Moreover, political circumstances must be created that favour global learning spillovers implicit to the transfer of experience and “know-how”. In this context, it is also relevant to investigate the potential synergies and trade-offs resulting from a joint adoption of policies that promote renewable-energy sources indirectly, e.g., the GHG-mitigation policies or the internalization of external costs. Implications of combining the renewable portfolio standard with ‘non-renewable’ policy instruments are discussed in Chapter 9.

8. Internalisation of external cost

Releases of air-polluting substances from energy systems are one the main threats to sustainability because of adverse impacts on the human health and ecosystems. Regulatory policy measures have been usually implemented in the industrialised regions to abate local air pollution. Direct environmental regulations typically involve emission standards and limits that are adopted through legislation procedures. Another policy strategy to address energy-related air pollution is to impose externality taxes on emissions such that the tax compensates for damages caused by emissions and discharges. By doing this, environmental taxes applied on a polluter attempts to internalize a so-called external cost within ordinary market conditions (Owen, 2004).

By definition, an external cost is a cost (or benefit) not included in the market price of the goods and services being produced, i.e., an externality represents a cost not borne by those who create the commodity. Taking an example from the electricity sector, if the emissions generated by a fossil-fuelled power plant contribute to costs associated with damages imposed on the society, and these costs are not taken into account in the price of electricity, externalities are introduced.

Environmental taxation as a tool for internalisation of external costs into the full energy-production cost is considered a potentially efficient policy instrument for reducing negative impacts of energy supply and use related to air pollution, as well as global warming. In addition, the approach of merging production (or generation) cost with external cost into a total specific cost serves as a comparative indicator for evaluation of economic and environmental performance of present and future energy technologies. Consideration of externalities, where quantified or quantifiable, might be useful for providing an indication of damages/benefits associated with different energy systems, for assessing trade-offs between different energy options, and for ranking energy technologies. Finally, accounting for external costs can serve as a basis for the introduction of economic policy instruments to reflect better the social costs of energy (Fouquet et al., 2001).

Although this kind of instrument omits other important aspects of the policy- and decision-making processes, for instance, the political and social acceptance of certain energy systems (Hirschberg et al., 2000), it is meaningful to investigate the long-term impacts of internalising externalities in the global energy system. The purpose of this chapter is not only to provide such an analysis by using the energy scenarios, but also to examine the possible co-benefits of controlling the local and regional air pollution for GHG-emission reduction and vice versa.

Estimation of environmental and non-environmental external costs is a complex task requiring expertise in order to analyse detailed energy chains and to give a credible monetary valuation of damages. External cost values used in this study have been derived from the outcomes of the European Commission (EC) ExternE Project (EC, 2003). The methodology used for this project applies the impact pathway approach, i.e., the pathways of polluting substances are followed from the release source to the point of damage occurrence. The consecutive negative impacts, or damages, are quantified using a damage function. This ‘bottom-up’ approach emphasizes detailed, site-specific characterization of technologies, thereby enabling consideration of every important stage in different energy chains, comparison between different fuel-cycles and different kinds of burden, as well as impact within a fuel-cycle. ExternE results include impacts of the following burdens, besides the air emissions: solid wastes, liquid wastes, risk of accidents, occupational exposure to hazardous substances, noise, others, e.g., exposure to electro-magnetic fields, emissions of heat (EC, 1999a).

Economic valuation of the damage to human health for the ExternE project was obtained by the “willingness-to-pay” (WTP) of the affected individual to minimize an adverse effects resulting from energy production by an actual power plant[7]. The underlying principle of the WTP-concept is to obtain a monetary value of preferences (in other words a demand) of a concerned individual to avoid a negative impact (EC, 1999b). Adding the amounts of all affected individuals would result in a value that a society attributes to the reduction of environmental impacts or to improve their own life-quality. The main advantage of the WTP approach lies in its foundation on the individual viewpoint of the concerned population.

Since the GMM model has a rich representation of the power-generation sector, including the ETL-specification of selected technologies, and because the assumptions on the external cost from the electricity production were provided (EC, 1999a), this analysis focuses primarily on the electric-power sector. No attempt has been made, however, to verify the external costs resulting from the EC-ExternE project as fully representing the environmental and health damages. The research questions addressed herein are as follows:

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[7] For the valuation of damages to items/commodities with exact market values, for example loss of crops, real market prices were used.

- What impacts could be expected if external cost from air pollution were fully internalized in the electricity sector?
- What are the consequences of extending the air pollution externalities to the damages related to CO_2 emissions?
- What are the implications of considering external cost for the competitiveness of electricity supply options?

Based on modelling results presented in Rafaj et al. (2005b) and Rafaj and Kypreos (2005), this chapter describes the structural, environmental, as well as economic impacts of a full internalisation of external costs in the electricity-generation sector, and is structured as follows. Section 8.1 defines the set of scenarios under survey, and elucidates the underlying assumptions for calculation and scaling of externalities. Section 8.2 summarizes the scenario results comparing the impacts of internalisation of both local and global externalities in the electricity sector. Key findings are reported for structural changes, environmental effects and policy cost. In Section 8.3, the results are summarised to provide a basis for policy insights and conclusions.

8.1. Scenarios

Two main scenarios were explored and compared to the Baseline scenario with the research objectives as specified above – a) the Local externality scenario with internalised external costs resulting from local air pollution (SO_2, NO_x, particulate matter), and b) the Global externality scenario where the external costs comprise both local air pollutants (SO_2, NO_x, PM) and emittants causing global climate change (CO_2). All of these scenarios include endogenous technological learning (ETL) and use assumptions of partial (economic) equilibrium. In addition to the main scenarios given in Table 19, two sensitivity scenarios are adopted for the Local externality scenario with different approaches to the regional scaling of external cost, as discussed in Section 8.1.2.

Scenario	Specification
Baseline	Baseline case, No local, No global externalities, with ETL
Local externality	External cost from local air pollution (SO_2, NO_x, PM) internalised in the electricity sector, Partial equilibrium, ETL
Local externality (GDP_{ppp})	The same as above, External cost from local air pollution scaled to regional purchasing power parity GDP per capita
Local externality (GDP_{mex})	The same as above, External cost from local air pollution scaled to regional GDP in market exchange rates per capita
Global externality	External cost from local air pollution (SO_2, NO_x, PM) and emissions causing global climate change (CO_2) internalised in the electricity sector, Partial equilibrium, ETL

Table 19. *Naming and description of the externality scenarios.*

8.1.1. External cost specification

Values of external cost, as quantified by the ExternE project are the basis of externality values used herein. The major impacts from the electricity sector identified by ExternE are those related to air pollutants, such as SO_2, NO_x and particulates. These impacts can have a transboundary character and impose damages mainly to the human health. Valuation of the mortality impacts in terms of damage costs is determined by a methodology based on the Value of a Life Year Lost (VLYL), which reflects the cost that a country is willing to pay to avoid a risk of premature death caused by air pollution. It has to be realised that the ExternE results are site- and technology-specific, and they are based on national studies for 15 countries of the European Union (EU).

For the purpose of internalisation of the external cost within the total electricity cost in different world regions outside of EU, the ExternE results were adjusted herein to reflect the GMM level of aggregation using the methodology developed for ACROPOLIS (2003). The determinants for scaling the externalities were the population density in regions; fuel quality expressed as the content of the sulphur in coal and oil; technology specification with respect to installation of the emissions control systems (e.g., $DeNO_x$, FDG); and finally, the possible improvement in conversion efficiency over the modelled time horizon. This scaling methodology assumes a pollutant-specific damage cost for a reference power plant in a reference EU-country, as is shown in Table 20.

Determinant for scaling	Unit	SO_2	NO_x	PM	CO_2
Average damage cost per pollutant	*€$_{1995}$/t*	8000	7000	14000	19
Population density adjustment factor (AF)	*High*	1.5	1.5	1.5	n.a.
	Medium	1	1	1	
	Low	0.75	0.75	0.75	
Reference thermal efficiency		**coal**	**oil**	**natural gas**	
	%	41	40	55	

Table 20. *Reference data for regional adjustment of the external cost. Source: ACROPOLIS (2003).*

While evaluation of externalities for air pollutants within the ExternE project is based on detailed bottom-up analysis, valuation of external cost for CO_2 emissions bears much larger level of uncertainty. External cost of global warming used in this study refers to the global warming damage cost of about 26$\$_{2000}$ per tonne of CO_2 (i.e., 95$/tC)[8], which is the median value of a range of recommended global-warming damage estimates reported by the ExternE project (EC, 1999c).

Table 21 summarises basic assumptions made for the adjustment of external cost in the GMM regions. The world regions are grouped in two population density categories according to present-day statistical data (GeoHive, 2003). The ASIA and OOECD regions are located within the category of High population density, and the remaining regions are assumed to have Medium population density. Given the high aggregation of regions in GMM, the correlation between average damage cost and population density bears a certain level of imperfection; furthermore, changes in the population density over time are not considered. Sulphur content in coal is assumed to be 1% in all world regions. Even though standardised statistical data are not available, a literature survey indicates that this value represents the typical average of all different coal types used for power production (Hinrichs, 1999). An optimistic assumption has been made that a global policy for imposing the external costs on electricity production starts from the same period (2010) in all regions. Simultaneously, it is expected that a global spill over of experience and know-how transfer from North to the South takes place.

Region	Population density	Sulphur content in coal [%]	Starting year of externality charges
NAME	Medium	1	2010
OOECD	High	1	2010
EEFSU	Medium	1	2010
ASIA	High	1	2010
LAFM	Medium	1	2010

Table 21. *Basic assumptions made for the regional external cost calculation.*

As mentioned earlier, external cost (*EXT*) was further scaled as a function of conversion efficiency so that exogenously given efficiency improvements over time for existing systems could be taken into account. Likewise, the future advanced technologies with very high efficiencies should not be penalized to the same extend as the existing ones. The following formula has been used for the cost scaling to the efficiency-increase:

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[8] Original values given in $€_{1995}$ (Table 20) have been converted into $\$_{2000}$ by using a conversion factor 1.37.

$$EXT_t = EXT_{original,t=0} * \frac{\eta_{original,t=0}}{\eta_t}, \text{ if } \eta_t > \eta_{original,t=0} \tag{24}$$

where η is the conversion efficiency of a respective power plant[9].

The resulting external costs applied for five world regions in GMM are displayed in Table 22. Ranges in the listed cost-values represent regional differences resulting from assumptions and scaling, as explained above. Costs are given in cents of US$$_{2000}$ per kWh.

Technology	ASIA				OOECD				NAME				EEFSU				LAFM			
	excl CO_2		*incl CO_2*		*excl CO_2*		*incl CO_2*		*excl CO_2*		*incl CO_2*		*excl CO_2*		*incl CO_2*		*excl CO_2*		*incl CO_2*	
YEAR	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050
Fossil-fuel based power plants																				
Coal conventional electric	18.96	11.55	20.76	13.20	11.79	11.55	13.49	13.20	8.32	8.14	10.01	9.80	9.29	8.58	11.08	10.24	13.51	8.14	15.30	9.80
Coal conventional electric with $DeSO_x$/$DeNO_x$	1.76	1.65	3.58	3.35	1.68	1.65	3.42	3.35	1.26	1.23	3.00	2.93	1.41	1.32	3.23	3.02	1.31	1.23	3.13	2.93
Coal conv. with $DeSO_x$/$DeNO_x$ and CO_2 seq	2.29	2.00	2.89	2.36	2.04	2.00	2.41	2.37	1.53	1.50	1.80	1.77	1.83	1.60	2.23	1.82	1.71	1.49	2.16	1.77
Coal advanced electric	2.41	2.13	3.84	3.39	2.41	2.13	3.84	3.39	1.79	1.58	3.22	2.84	1.93	1.70	3.36	2.96	1.78	1.57	3.21	2.83
Coal advanced electric with CO_2 seq	2.83	2.50	3.04	2.65	2.83	2.50	3.04	2.64	2.10	1.85	2.17	1.89	2.26	2.00	2.32	2.05	2.08	1.84	2.16	1.88
Coal IGCC	1.02	0.66	2.95	2.35	1.02	0.66	2.95	2.35	0.76	0.51	2.68	2.20	0.78	0.53	2.71	2.22	0.76	0.51	2.69	2.20
Coal IGCC with CO_2 seq	1.20	0.78	1.66	1.32	1.20	0.78	1.66	1.32	0.89	0.60	1.29	1.16	0.92	0.62	1.31	1.17	0.90	0.60	1.30	1.16
Natural Gas Combined Cycle (NGCC)	1.09	0.31	1.70	0.89	0.35	0.31	1.00	0.89	0.27	0.25	0.89	0.83	0.82	0.25	1.47	0.83	0.82	0.25	1.47	0.83
NGCC with CO_2 sequestration	1.29	0.34	1.53	0.73	0.39	0.34	0.84	0.73	0.31	0.28	0.78	0.68	0.31	0.28	0.78	0.68	0.31	0.28	0.78	0.68
Gas turbine	1.69	1.69	2.64	2.64	1.69	1.69	2.64	2.64	1.20	1.20	2.14	2.14	1.20	1.20	2.14	2.14	1.20	1.20	2.14	2.14
Gas steam conventional	2.96	1.48	3.85	2.31	1.56	1.48	2.43	2.31	1.14	1.05	2.04	1.88	2.02	1.05	2.90	1.88	2.04	1.05	2.93	1.88
Cogenaration gas turbine	1.76	1.76	2.75	2.75	1.64	1.64	2.56	2.56	1.25	1.25	2.24	2.24	2.28	1.25	3.26	2.24	1.25	1.25	2.24	2.24
Gas fuel cell (GFC)	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83
Hydrogen fuel cell (CHP) in industry (H_2FC)	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83
Hydrogen fuel cell (CHP) in res&com. (H_2FC)	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83	0.28	0.28	0.83	0.83
Oil electric	5.87	1.89	7.22	3.10	5.16	1.89	6.69	3.10	3.96	1.46	5.31	2.81	3.50	2.16	5.03	3.38	3.50	1.31	5.03	2.52
Nuclear and renewable power plants																				
Nuclear plant - Light Water Reactor (LWR)	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48
Advanced new nuclear power plant (NNU)	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48	0.46	0.46	0.48	0.48
Hydro-electric plant (small and large)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Solar photovoltaics (SPV)	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28
Solar thermal electric	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28	0.09	0.09	0.28	0.28
Wind turbine	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Biomass power plant	0.28	0.28	0.41	0.41	0.28	0.28	0.41	0.41	0.28	0.28	0.41	0.41	0.28	0.28	0.41	0.41	0.28	0.28	0.41	0.41
Geothermal electric	0.14	0.14	0.41	0.41	0.14	0.14	0.41	0.41	0.14	0.14	0.41	0.41	0.14	0.14	0.41	0.41	0.14	0.14	0.41	0.41

Table 22. *External costs applied for five world regions in GMM in ¢/kWh.*

8.1.2. Alternative approaches in externality valuation and scaling

One of the drawbacks of the externality-values scaling described in the previous section is that the average unit damage cost per ton of pollutant is estimated for typical conditions in Western Europe. The WTP to avoid damages resulting from air pollution, however, may vary

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[9] Sample calculation for a pulverised coal power plant with 0% $DeSO_x$, 50% $DeNO_x$, 80% DEDUST, η_{2010} = 37%, η_{2050} = 38%, Sulphur content = 1%.

<u>Medium population density</u> (Adjustment factor *AF* = 1)

EXT_{2010} = 9.9 ¢/kWh * 1 = 9.9 ¢/kWh

EXT_{2050} = EXT_{2010} * (0.37/0.38) * 1 = 9.6 ¢/kWh

<u>High population density</u> (Adjustment factor *AF* = 1.5)

EXT_{2010} = 9.9 ¢/kWh * 1.5 = 14.8 ¢/kWh

EXT_{2050} = EXT_{2010} * (0.37/0.38) * 1.5 = 14.4 ¢/kWh among countries with the affected populations having different incomes. The VLYL value used for monetisation of the mortality impacts, which is based on the Value of Statistical Life (VSL), therefore, needs to account for these differences if the damage costs estimated for Europe are applied to the regions with unknown WTP.

The method proposed by EC (1998b) to adjust the ExternE-results to the welfare situation of regions other than EU implies that the pollutant-specific damage cost are multiplied by the ratio of purchasing-power-parity (ppp) adjusted GDP (GDP_{ppp}) of new location to the GDP_{ppp} of the EU. This method has been applied in studies aimed at the estimation of external cost in developing countries, e.g., Markandya and Boyd (1999) and Hirschberg et al. (2003). The latter cited study for China adopted a GDP_{ppp}–based scaling factor of 0.143 (or a reduction by factor of 7) to adjust the unit damage cost estimated for typical European conditions.

The same approach for external cost scaling has been used in the sensitivity scenarios Local externality (GDP_{ppp}) and Local externality (GDP_{mex}). The former scenario adjusts the external costs provided in Table 22 by using the ratio of GDP_{ppp} per capita, while in the latter case the per-capita GDP in market exchange (mex) rates (GDP_{mex}) has been used:

$$EXT_{t,r} = EXT_{t,r}^{original} * \frac{GDP_{ppp,t}^{r}}{GDP_{ppp,1995}^{EU}}, \text{ or } EXT_{t,r} = EXT_{t,r}^{original} * \frac{GDP_{mex,t}^{r}}{GDP_{mex,1995}^{EU}} \tag{25}$$

The GDP_{ppp} and GDP_{mex} projections out to 2050 for the GMM regions correspond to those reported by IPCC (2000) for the marker B2 scenario. The resulting scaling-factors applied in the sensitivity scenarios are summarized in Table 23.

Region	Type of adjustment	2010	2020	2030	2040	2050
NAME	GDP_{ppp}/cap	2.0	2.2	2.3	2.5	2.8
	GDP_{mex}/cap	1.6	1.7	1.9	2.0	2.2
OOECD	GDP_{ppp}/cap	1.3	1.5	1.6	1.7	1.8
	GDP_{mex}/cap	1.3	1.4	1.6	1.7	1.8
EEFSU	GDP_{ppp}/cap	0.4	0.5	0.7	0.9	1.1
	GDP_{mex}/cap	0.1	0.2	0.3	0.6	0.8
ASIA	GDP_{ppp}/cap	0.3	0.4	0.5	0.6	0.7
	GDP_{mex}/cap	0.1	0.2	0.2	0.3	0.4
LAFM	GDP_{ppp}/cap	0.2	0.2	0.3	0.4	0.5
	GDP_{mex}/cap	0.1	0.1	0.2	0.2	0.3

Table 23. *Regional adjustment of external cost to GDP. Adopted from IPCC (2000) and IEA (2004c).*

8.1.3. Treatment of external costs in MARKAL model

As discussed above, an external cost of electricity is introduced if the emissions generated by power plants imply damages to the society and the invoked cost is not a part of the market price of electricity. Usually, the production cost per unit of electricity is expressed as function of the capital cost, the fixed and variable O&M cost, and the fuel cost (see Section 8.2.4.1, Box 2, and Equation B1). The ExternE values estimate the external costs needed to compensate for the health and environmental damage and thereby yields a full-cost pricing of electricity. These extra charges per unit of kWh generated by region and technology have to be included in the total electricity-generation cost, as well as in the total energy-system cost.

External costs (*EXT*) are implemented in the GMM model by multiplying the amount (*Q*) of electric power generated (i.e., kWh) from each power plant (*j*) during each time period (*t*) in each region (*r*) with corresponding external cost (i.e., ¢/kWh). In this way, it is assured that the matching external costs are directly charged to every unit of output from each power plant. The sum of discounted annual externality charges for every region in GMM is reflected in the total discounted system cost (i.e., the objective function used in GMM) in the externality case (*extern*):

$$Z_{extern} = Z + \sum_{t} EXT_t \cdot ypp \cdot Q_t \cdot \left(1 + d\right)^{-t} \tag{26}$$

where Q_t stands for the total quantity of electricity generated by all technologies, as defined in Section 7.1.3, Equation 21.

An alternative approach that could be used to integrate the environmental damages into the MARKAL is based on the damage function (*DAM*). This approach has been followed by Van Regemorter (2004) and applies the damage per polluting substance (*env*) as an environmental tax levied on the entire energy system. The emission-specific environmental tax (*DAX*) would be charged per unit of pollutant emitted (*EM*), e.g., 8000\$/tSO_2, which would affect all emitting technologies in all sectors present in the energy system of each region (i.e., including refineries, demand devices, transport sector, etc.).

$$DAM_{t,r} = \sum_{env} DAX_{t,r,env} \cdot EM_{t,r,env} \tag{27}$$

Because this analysis is explicitly focused on the externality impacts on the power generation sector, the approach explained in the previous paragraph has been chosen.

The GMM model has different response options for the extra charges imposed on the electricity sector with the aim of minimising the total energy system cost: a) to pay (or not) an external charge on power production from a given technology; b) to install (or not) a (costly) system with $DeNO_x$, $DeSO_x$, DEDUST or CO_2-capture & sequestration; c) to reduce (or not) the energy/electricity consumption in different demand sectors and to substitute the electricity by other fuels; d) to apply (or not) the inter-fossil fuel switching and technological change for technologies with lower external cost (renewables and nuclear power plants).

8.2. *Scenario Results*

The following section describes the scenario results in terms of electricity production, primary- and final-energy demand, and describes changes in the global energy-related emissions. Cost impacts are discussed with respect to electricity generation cost and total system cost. In addition, changes in total damages based on different approaches for regional externality adjustment are reported.

8.2.1. Structural changes

8.2.1.1. Electricity generation

Internalising the external costs of air pollution and CO_2-emissions into electricity production cost influences significantly the structure of the power generation mix. In the Local externality scenario, coal remains the major contributor to total power production, although, its share is reduced in 2030 by 55% and in 2050 by 27% relative to the Baseline (in absolute terms by 9900 TWh/yr and 9100 TWh/yr). Moreover, the conventional pulverised coal combustion is replaced by advanced coal plants (i.e., supercritical plants, PFBC, IGCC) and pulverised coal systems with SO_2 and NO_x emissions control, i.e., Flue Gas Desulfurization-FGD, low-NO_x burners, etc. The NGCC plants with other natural gas based systems increase their relative share in power production to a level of 37% and 25% of the total electricity supply in 2030 and 2050. In absolute terms an increase in the total power generation from NGCC by 1300 TWh/yr is reported in the end of horizon. Finally, the share of renewables and nuclear plants in 2050 is increased by 28 % relative to the Baseline case because of lower external costs charged to these systems.

As is shown in Figure 57, changes in the electric power mix become more pronounced in the Global externality scenario. The generation from coal-based technologies reaches only 19%, while natural-gas fired power stations produce around 33% of total electricity in 2050. The

IGCC systems with CO_2-capture become competitive and penetrate the market between 2030 and 2050 at considerable levels. Nuclear energy supplies almost 20% of electricity in 2050; both the Light Water Reactor (LWR) and advanced nuclear plants (NNU) play more significant role in the power supply throughout the time frame examined after implementing external cost as compared to the Baseline. In the Global externality scenario, technologies based on hydroelectric and non-hydroelectric-renewable sources contribute 28% of total generation by the year 2050.

Because of rising cost of electricity, the overall power generation in 2050 is decreased by 4% in the Local externality scenario and by 9% in the Global externality scenario, relative to the Baseline (effect of reduced demand for electricity due to partial equilibrium).

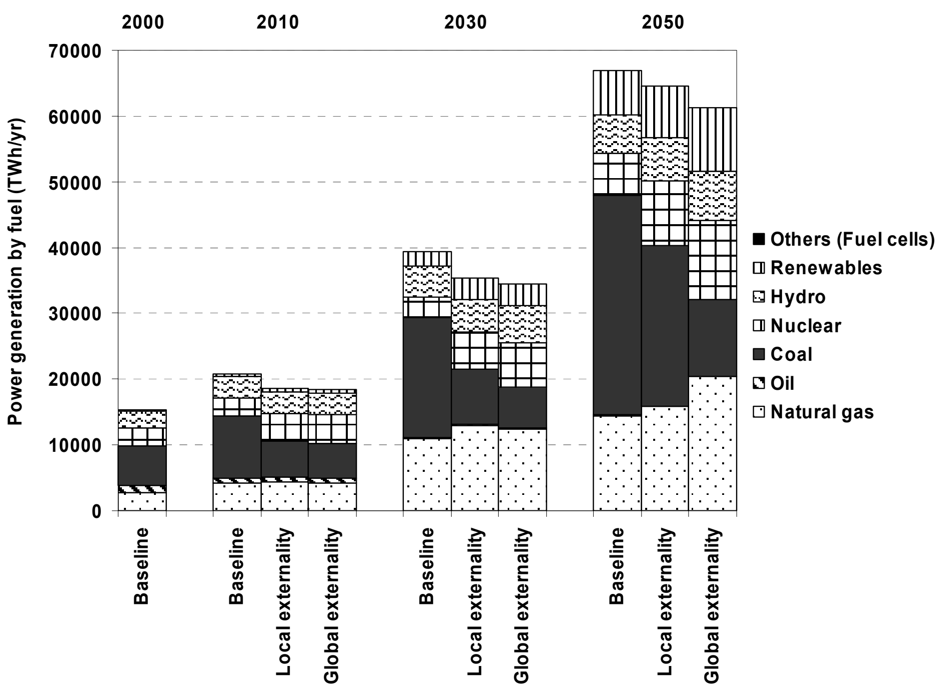

Figure 57. *Development in global electricity production by fuel under the Baseline and externality scenarios.*

The main impact of the internalisation of local and global external costs on the power sector is the massive elimination of conventional coal power plants from the generation mix, and the accelerated market penetration of advanced systems with low SO_2/NO_x emissions rates[10]. This behaviour of the energy system is the strongest in the region of ASIA, which relies on the electricity-supply options based on coal combustion. Additionally, low external cost increases

[10] Note that the modelling approach used does not allow for retrofits of existing systems by the installation of "add-on" scrubbing equipments. Conventional coal-fired plants and power plants with $DeSO_x/DeNO_x$ are represented as independent systems.

the competitiveness of nuclear power plants and renewables as compared to the Baseline. In the sensitivity scenarios Local externality (GDP_{ppp}) and Local externality (GDP_{mex}), where the local external cost is rescaled according to the GDP-development in the world regions, a similar trend is observed over the full time horizon. In other words, despite the fact that external cost are significantly lower after being adjusted to GDP_{ppp} and GDP_{mex} per capita in regions of ASIA, LAFM and EEFSU as compared to the initial 'population-density' scaling, the unit damage cost assumed for these regions is high enough to eliminate the most polluting coal-fired plants from the supply mix.

A feedback from the lower external charges in terms of a less rapid decrease in the coal-based power generation, however, occurs in the Local externality (GDP_{mex}) scenario, as is shown in Figure 58. This feedback is particularly strong for the region ASIA, and is explained by the external cost levels that are 10 times lower if scaled according to GDP_{mex}/cap as compared to the Local externality case (see Table 20 and Table 22). These results may have important policy-implications, since it suggests that in the countries of ASIA region an externality tax level of about 1000\$/tSO_2 would be sufficient to achieve a substantial emission-reduction effect. Similar findings are presented by Kypreos and Krakowski (2005) for the impacts of externalities in the China's electricity sector.

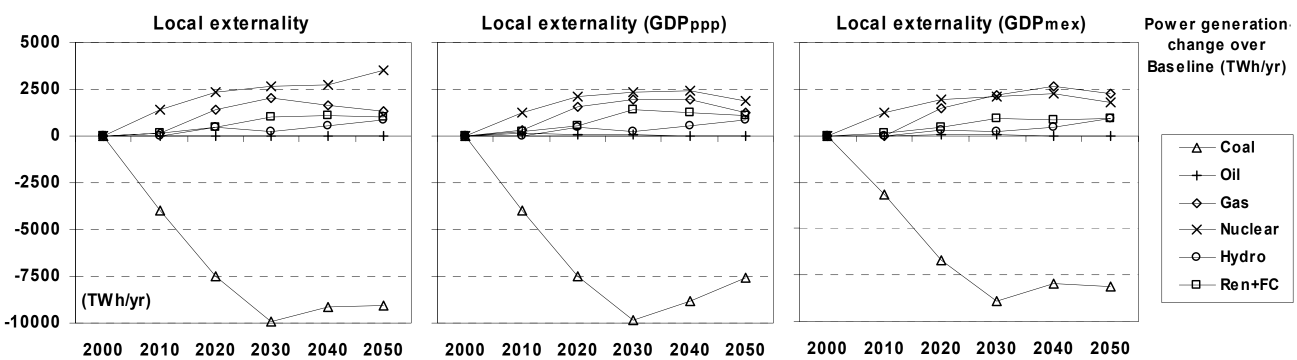

Figure 58. *Change in global power generation by fuel with respect to the Baseline under scenarios assuming different scaling of local external cost.*

Figure 59 illustrates the power generation profile in 2050 for main scenarios considered. Coal-based technologies with $DeSO_x/DeNO_x$ systems produce a considerable amount of electricity in the case where local external costs are incurred, but this amount is more than three times less than computed for the Global externality scenario. On the other hand, when global external costs are imposed, the systems with CO_2-capture become competitive, and the IGCC technology with carbon capturing and sequestration is the largest coal-based power producer at the global level in 2050. This finding suggests that internalised external cost comprising both air pollutants and CO_2-emissions makes the IGCC with CO_2-removal an attractive technological option for carbon mitigation strategies. Similarly, the share of NGCC systems in 2050 increases significantly under externality scenarios relative to the Baseline development. The competitiveness of technology options on the basis of generation costs is discussed further in Section 8.2.4.1.

In both externality scenarios the growth in renewable-energy and nuclear electricity sources is controlled by the exogenous bounds and assumed growth rates, as is described in Section 3.2. The results of this analysis indicate a substantial increase in generation from conventional as well as advanced nuclear power plants in all regions modelled in GMM. On the other hand, the growth in hydropower production is most pronounced in the ASIA and LAFM regions, where the total generation is close to assumed exploitable limits. Similarly, the power production from wind turbines in externality scenarios is approaching its technical potential, as specified through an upper bound in GMM (see Section 7.1.1). Furthermore, the growth in generation from wind turbines in the Global externality scenario reaches the constraint imposed on generation from intermittent sources of electricity, which explains a slightly lower contribution in absolute terms of wind power to the generation profile in 2050 relative to the Local externality scenario.

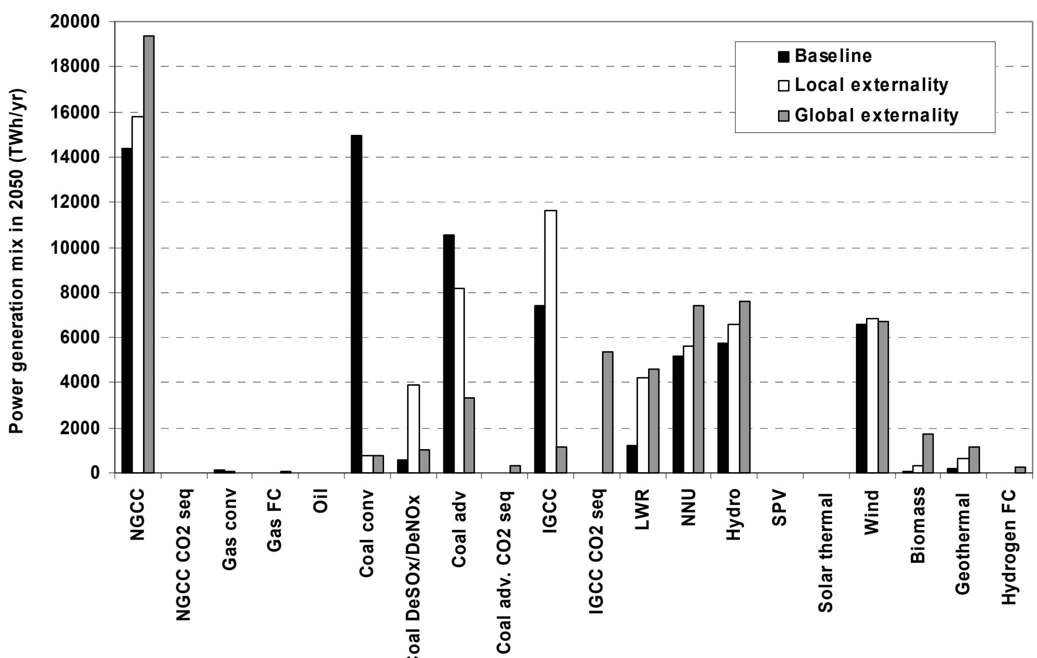

Figure 59. *Contribution of technologies to the global electricity generation mix in 2050 in the Baseline and externality scenarios. For nomenclature, see Table 8.*

8.2.1.2. Primary energy consumption

Total global primary energy consumption decreases if external costs of power generation are included. In the year 2050, reductions by 2% to 3% in total primary energy consumption relative to the Baseline scenario in the externality scenarios are reported. This behaviour is a result of the use of the fossil equivalent for calculation of the contribution of non-fossil sources to primary energy consumption and because of the switch to fuels other than electricity in the final energy demand. As shown in Figure 60, the Local externality scenario is characterised by a large reduction in coal consumption and this reduction is substantial already during the period 2010-2030. Coal demand is replaced primarily by nuclear energy, and the rapid reduction in coal use is balanced with rising use of natural gas, oil and renewable power.

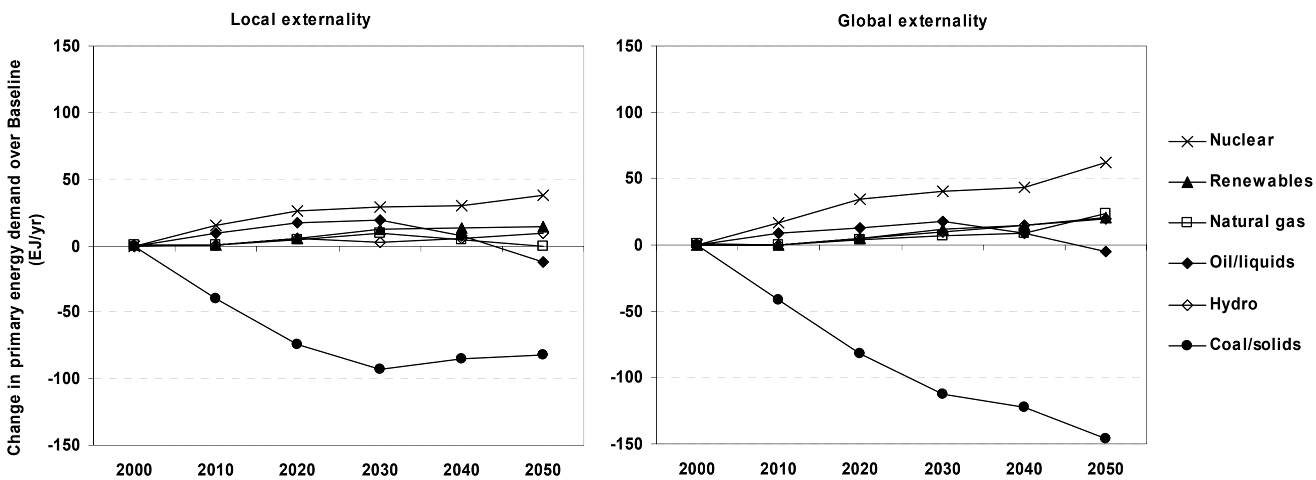

Figure 60. *Change in global primary energy consumption over the Baseline for the externality scenarios.*

This trend becomes even more obvious in the Global externality scenario, where coal use (mainly for power generation) is substituted with nuclear energy, natural gas, as well as with oil between 2010-2040, which is a reflection of the inter-fossil fuel substitution. A large increase in renewable electricity consumption at the end of the time horizon is projected. Increases in natural gas use over the modelled horizon under the externality scenarios are associated with a growth in power generation from the NGCC systems. Changes and fuel switching in the primary energy demand for the Global externality scenario are most significant towards the end of time horizon. This observation is related to a larger penetration of low-emitting technologies induced by externality charges, and further accelerated by cost reducing effects of ETL. It should be noted that the replacement of coal use for power generation goes along with given declination rates assumed for retirement of conventional coal plants without emission control.

8.2.1.3. Final energy demand

In both externality scenarios, the total final energy consumption decreases (2 – 3%) compared to the Baseline scenario in 2050. Comparison of shares in the final-demand fuel mix summarised in Figure 61 shows that the consumption of electricity and natural gas is reduced towards the end of time horizon relative to the Baseline case, while the demand share of other fuels increases. Reduction in the use of natural gas is related to the increased gas consumption in the electricity sector.

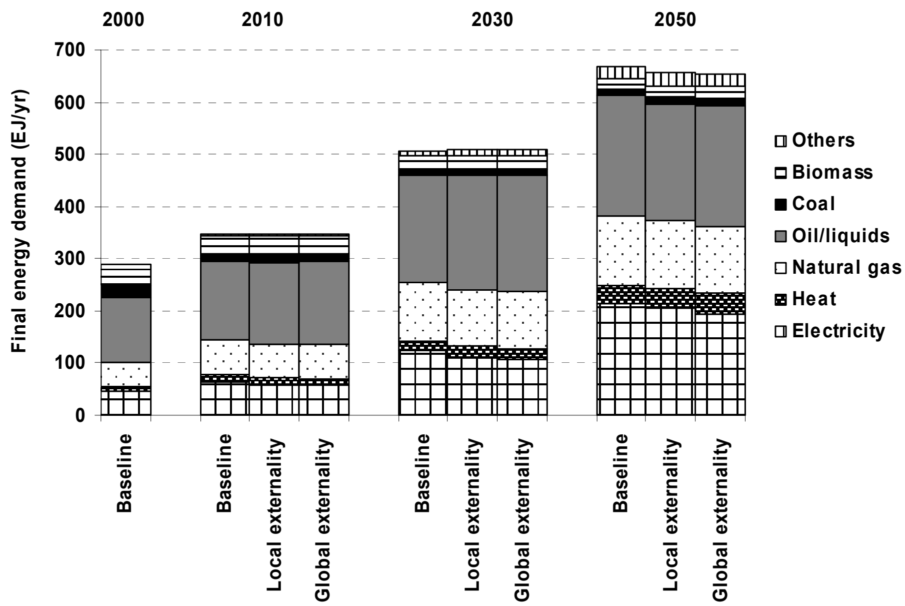

Figure 61. *Time evolution of fuel shares in total final energy demand in the Baseline and in externality scenarios.*

The induced electricity-price increase results in electricity demand reductions and substitution of electricity for other fuels by the end-users. The price-elasticity for the attendant end-use demand reductions varies between -0.20 to -0.30 for demand sectors represented in GMM (see Table 7). Figure 62 illustrates changes of the final electricity demand in externality scenarios compared to the Baseline scenario.

While the consumption of electricity is reduced in both industrial and residential&commercial sectors, the transport sector is not affected. The largest reduction is projected in the industrial sector, since this sector has the greatest ability to switch from electricity to other fuels.

The most significant electricity-demand reductions are observed during the period 2020-2040 and are associated with premature closing of existing electricity sources based of coal combustion during this period. The electricity-demand reductions are lowered in 2050, and represent for the industrial sector a relative decrease over the Baseline case of 9% in the Local and 24% in the Global externality scenario.

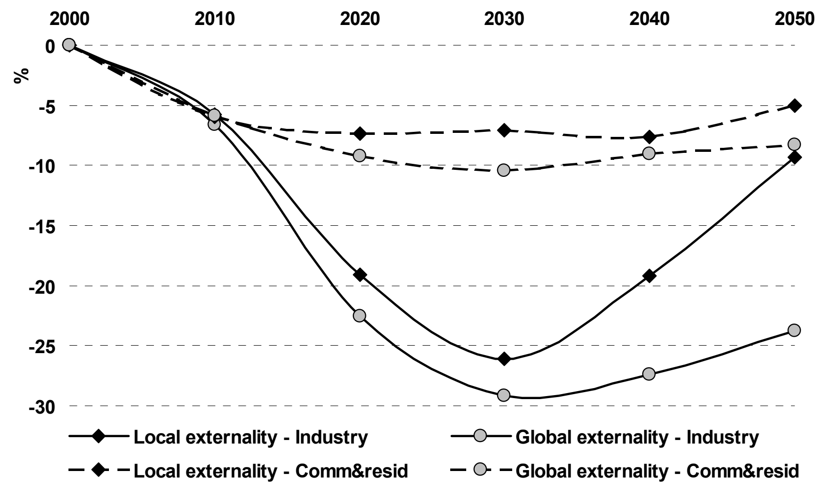

Figure 62. *Change in global electricity consumption relative to the Baseline in the industrial and residential&commercial demand sectors for the externality scenarios.*

8.2.2. Environmental impacts

Internalisation of external cost into the total production cost of electricity leads to rapid emission-reducing effect in both externality scenarios. Figure 63 represents the relative change of global air emission over the Baseline scenario. For all considered emissions (CO_2, SO_2, NO_x), the most significant reduction occurs within the period 2000 to 2030 and is associated with a substantial fallback of coal-based power generation implicit to the premature retirement of coal-fuelled plants operated without SO_2/NO_x control. Until the year 2040, the emission reduction is partly stabilised.

At the end of the time horizon, different developments can be observed in CO_2 emissions and air pollutants. As the (learning) technologies based on fossil fuels coupled with CO_2-removal begin to penetrate the market between 2040-2050, total CO_2 emissions are reduced by 26% in the Global externality scenario, as compared to the Baseline case. On the other hand, the substantial decrease in SO_2 and NO_x emissions relative to the Baseline scenario, reported for periods by 2040, is less pronounced in the end of horizon. This trend is explained by an increasing market share of the advanced fossil-fuelled systems with ETL option (e.g., NGCC, advanced coal, IGCC) by 2050 as compared to the earlier periods.

Significant CO_2-emission reduction for the Local externality scenario suggests that important ancillary benefits can be expected from policies that directly address other environmental issues than CO_2-mitigation.

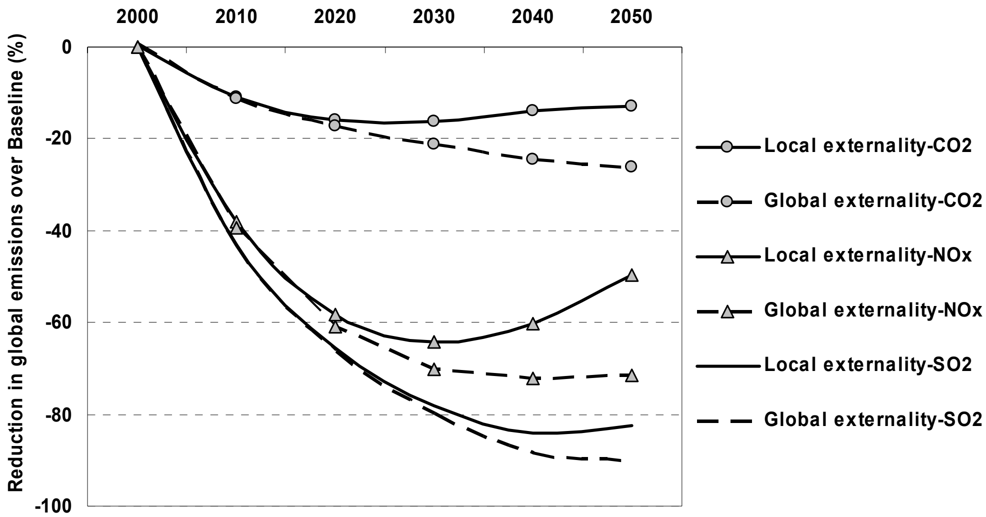

Figure 63. *Change in the global air emissions in the externality scenarios relative to the Baseline.*

8.2.2.1. Global CO_2 emissions

While total global carbon-emissions under the Baseline conditions rise during the full computational period at an annual rate of 1.97%/yr and reach a level of 16.8 GtC/yr in 2050, total emission levels are lowered by 13% in 2050 for the Local externality scenario. The most significant reductions for the Local externality scenario occur between 2010 and 2020. Subsequently, the annual growth rate is reduced to 1.5%/yr. A similar CO_2-emission trajectory is observed for the sensitivity scenario Local externality (GDP_{mex}), in which a less pronounced drop in consumption of coal for power production is projected as compared to the Local externality scenario.

In the Global externality scenario, the annual growth in CO_2 emissions is 1.2%/yr and culminates around the year 2030. As is shown in Figure 64, the reduction in the growth of carbon emissions appears around 2040 and is associated with the market penetration of low-carbon technologies, for instance, nuclear power, renewables and fossil-fuelled systems with CO_2-capture. The global emission level of 12.4 GtC/yr is projected at the end of the time horizon.

The results presented in this section indicate that the policies internalising local and global external cost, as applied only to the power sector and as formulated in this modelling exercise, might not be sufficient to reduce global carbon emissions to levels needed for 550 ppmv target discussed in Chapter 5, or, that the efforts to curb CO_2 emissions will have to be accelerated further in the second half of the 21st century.

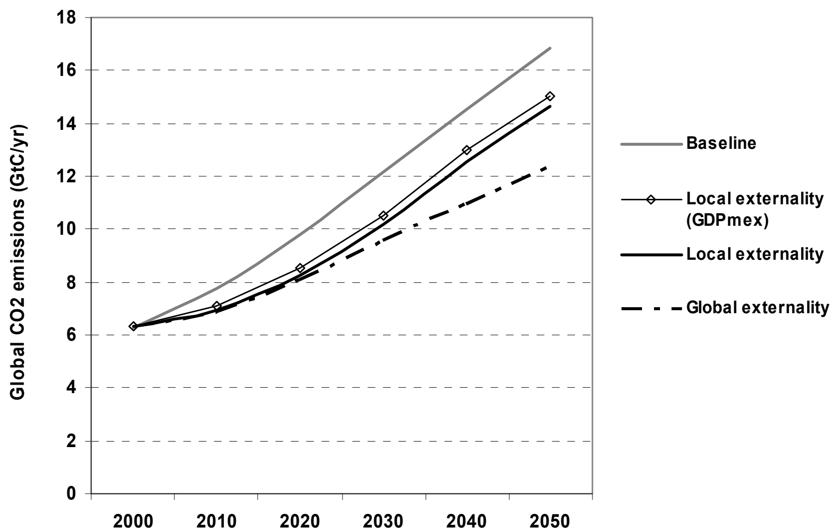

Figure 64. *Development of global CO_2 emissions under the Baseline and externality scenarios.*

8.2.2.2. Break-down of CO_2 reduction components

The decarbonisation effect of the policy comprising internalisation of external cost is demonstrated by a break-down of the different CO_2 reduction components, as is shown in Figure 65. The same carbon-reducing components were considered as in Section 5.2.2.2. In both externality scenarios, the inter-fossil fuel switching plays a dominant role in carbon mitigation and contributes 50% to 55% of CO_2 reduction in 2050. The important role of a larger deployment of nuclear energy is reflected in the CO_2-emissions reducing effect, since in the time period 2010-2050 the nuclear energy contributes to 16-29% of the total reduction. Carbon removal from fossil-fuelled power plants plays a significant role in the Global externality scenario. The share of carbon capture and storage in the overall CO_2-mitigation process in 2050 corresponds to 20% and the cumulative carbon removal from 2010 to 2050 is 17.6 GtC.

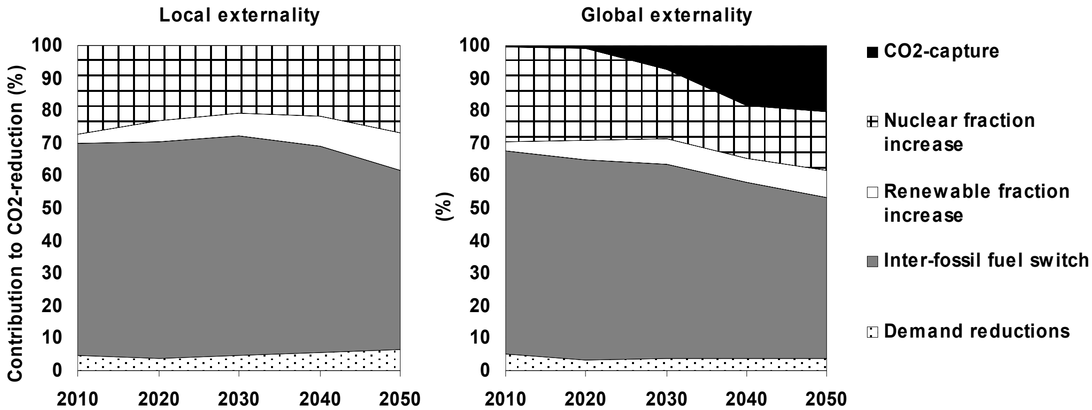

Figure 65. *Break-down of CO_2 reduction components under externality scenarios.*

8.2.2.3. Emissions of air pollutants

Figure 66 shows total SO_2 and NO_x emissions from the power production. To illustrate the effect of external cost on the emission reduction, no explicit local or regional air pollution mitigation policies are considered across the world regions in the Baseline scenario. The reference SO_2-emissions peak in the period 2030-2040 at the rate of 104 Mt SO_2/yr in the Baseline, with the region of ASIA being the main contributor to the emissions level. With a lowered share of conventional coal plants, overall sulphur emissions decrease significantly until 2050.

As the desulphurisation systems together with advanced coal and IGCC technologies displace the conventional coal-based technologies from the energy system in the externality scenarios, the sulphur-emission reduction effect is substantial. Electricity-related emissions of NO_x increase in the Baseline scenario until 2040 and then are stabilised at the annual rate below 50 Mt NO_x per year. In the externality scenarios, no substantial increase in the NO_x emissions is observed until 2040. Towards 2050, the level of NO_x grows by 20% in the Local externality scenario relative to 2040, because of increased penetration of new fossil-based technologies.

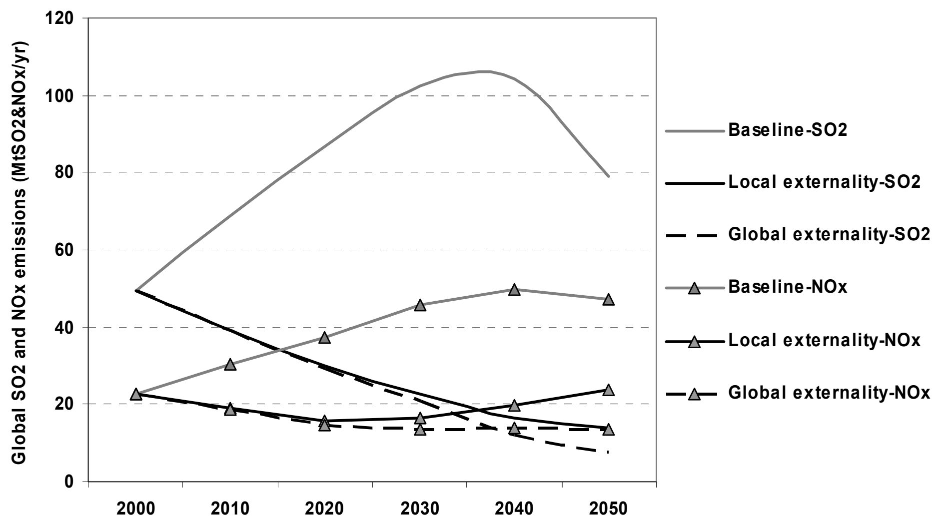

Figure 66. *Development of SO_2 and NO_x emissions from the power generation sector under the Baseline and externality scenarios.*

8.2.3. Global indicators

A set of indicators for the global RES, as defined in Chapter 4, is shown in Figure 67 for the Baseline and externality scenarios. Similar reductions in the primary energy intensity (i.e., the primary-energy consumption per unit of GDP) over the Baseline case are reported for the externality scenarios, giving an annual declination rate of -1.1%/yr between 2010 and 2050. The reduction in energy intensity over the Baseline occurs as early as in 2010 and is associated with the energy consumption decrease and technological changes invoked by the externality charges in the electricity sector.

The carbon intensity after 2020 shows different trajectories in the externality cases, with the annual declination rate of –0.1%/yr in the Local externality scenario, and –0.8%/yr in the Global externality case, respectively. The strong reduction in carbon intensity under the Global externality scenario when compared to the Local externality case is connected to the increasing market shares of the low-CO_2 technologies in the electricity-production sector, which is consistent with the results discussed in Section 8.2.1.1.

The remarkable decarbonisation effect of the policies that internalise external cost in the price of electricity is further demonstrated in Figure 67c, where the indicator of CO_2 emissions per unit of GDP is used. This indicator shows a declining trend, which continues over the computational period in both externality cases; the annual declination rates for the Local externality and Global externality scenarios are of –0.9%/yr, and –1.4%/yr, respectively.

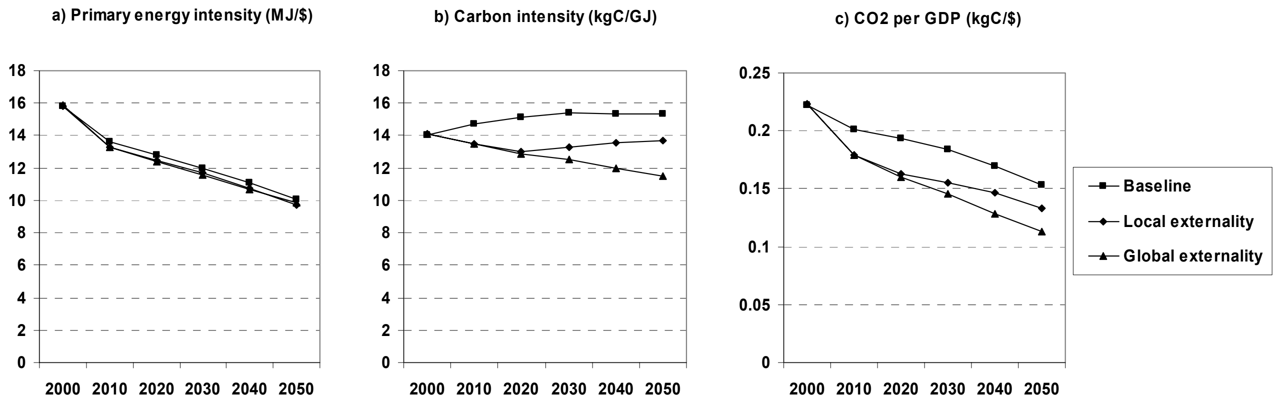

Figure 67. *Development in selected global indicators under the Baseline and externality scenarios.*

8.2.4. Cost impacts

8.2.4.1. Electricity generation cost analysis

To evaluate the competitiveness of different power generation technologies, a simplified calculation of electricity generation cost has been performed. The calculation assesses the impacts of internalisation of different externality modes on total production cost, as well as the effect of 'learning-by-doing' on the cost development over time. The methodology used for calculation of electricity generation cost is elaborated in Box 2.

Figure 68 summarizes results of the total generation cost calculation for the Baseline and externality scenarios for the present situation and cost projection for the year 2050. The ASIA region is taken as an example for the analysis. The Baseline scenario results in 2000 indicate that without external cost, conventional pulverised coal, NGCC and coal-cased power plants with $DeSO_x/DeNO_x$ are the cheapest alternatives at 3.5, 3.6 and 4.1 ¢/kWh, respectively.

The projected generation costs in the Baseline scenario in 2050 reflect the change in fuel cost, the impact of ETL towards reduction of investment cost with accumulation of installed capacity by 'learning' technologies in 2050, expected improvement in the conversion efficiency, and a higher average load factor. The least cost systems are wind turbines, IGCC and advanced coal power plants, with projected generating cost at the level of 2.4, 2.8 and 3.1 ¢/kWh, respectively. Clearly, the cost reduction for advanced technologies projected in the Baseline scenario is related to the technology-specific assumptions about learning potential. Investment cost reduction inherent to the application of the LBD-concept requires policy-actions and learning investments in favour of advanced generation systems.

BOX 2: Calculation of the electricity generation cost

Total electricity generation cost (also referred to as levelized cost of energy or busbar cost) for a technolgy (*j*) is calculated according this formula adopted from Drennen et al. (2003):

$$TGC = \frac{I * CRF}{Q} + \frac{FIXO\&M}{Q} + \frac{VARO\&M}{Q} + \frac{F}{Q} + \frac{EXT}{Q} \qquad \text{(B1)}$$

where:

I	= Capital investment cost
CRF	= Capital recovery factor
Q	= Annual plant output (kWhr)
$FIXO\&M$	= Fixed O&M cost
$VARO\&M$	= Variable O&M cost (including CO_2-storage cost)
F	= Fuel cost
EXT	= External cost

$$CRF = dr * \frac{(1+dr)^n}{(1+dr)^n - 1} \qquad \text{(B2)}$$

where:

dr	= (real) discount rate
n	= plant life time

Calculation of specific investment cost for the learning technologies in 2050 follows the approach described by Barreto (2001):

$$I_{2050} = I_0 * \left(\frac{CC_{2050}}{CC_0}\right)^{-b} \qquad \text{(B3)}$$

where:

I_{2050}	= Specific investment cost in 2050
I_0	= Specific investment cost at the starting point when technology is introduced into the system
CC_{2050}	= Cumulative capacity of the technology in 2050
CC_0	= Cumulative capacity of the technology at the starting point
b	= Learning index

$$-b = \frac{\ln pr}{\ln 2} \quad \Rightarrow \quad pr = 2^{-b} \qquad \text{(B4)}$$

where:

pr is the progress ratio, or the rate at which the cost declines each time the cumulative capacity doubles. An alternative is to specify the learning rate (LR), which is $LR = 1 - pr$; see further details in Section 3.3.

Applying policies that internalise external cost related to air pollution in the generation cost, the competitiveness of technology portfolio changes towards the end of the time horizon. The least cost options in this case in 2050 are the wind turbines, IGCC and advanced nuclear plants, with total generation cost of 2.5, 3.5 and 4.0 ¢/kWh, respectively. High external cost makes the coal-based power plant without emission control the most expensive electric-power source among fossil-fuelled systems, which explains the massive elimination of this technology from the generation mix.

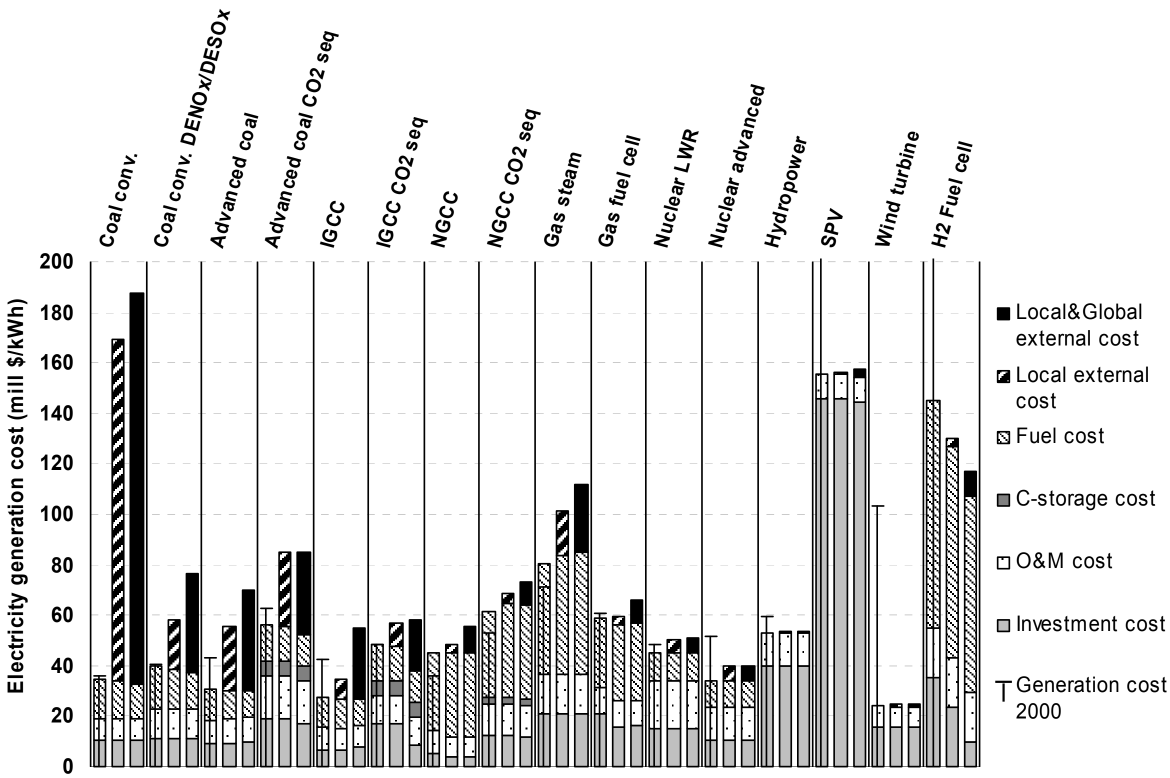

Figure 68. *Break-down of the cost components for power generation by scenarios in 2050 (example region ASIA) at 5% real discount rate. Bars from left to right represent the Baseline, Local externality and Global externality scenarios. [1 $ = 100 ¢ = 1000 mills]*

In the case of internalised global externalities, the most competitive systems are those with low- or zero-emission rates: the wind turbines (2.5 ¢/kWh), followed by advanced and conventional nuclear power plants (4.0 - 5.1 ¢/kWh), and hydropower (5.4 ¢/kWh). The total cost of electricity from IGCC with CO_2-capture is about 5.8 ¢/kWh. Although the generation costs in both externality scenarios increase when compared to the Baseline scenario, the higher competitiveness of advanced fossil-fuelled systems, advanced nuclear, and renewable energy technologies implies a decreased dependency of the electricity sector on the fossil-fuel supplies.

The regional impacts of the policy instrument that internalises external cost into the power generation cost, as implemented in this analysis, are portrayed by comparing changes in the shadow price of electricity in regions represented in GMM[11]. Table 24 shows that the range of increases in the average shadow prices can be large (from 0.4 to 6.7 ¢/kWh), depending on

[11] The shadow price of electricity resulting from the model run is equal to the marginal value of the electricity for the regional energy system as a whole. There are six electricity prices, one for each time-slice defined in GMM (i.e., Summer day; Summer night; Winter day; Winter night; Intermediate day; Intermediate night). This provides a composite electricity price which is the average of the 6 electricity shadow prices, and which represents the price of a kWh produced throughout the 6 time-slices (EIA, 2003b).

the time period and the region. More relevant than the absolute numerical results is that the price increase is significantly higher in both externality scenarios for regions largely relying on the coal-based electricity production, e.g., the ASIA region. The incremental increase in the shadow price decreases over the computational time frame in most of the regions. Large increase in the price in periods 2010-2020 suggests that the timing of implementation of the policy is particularly important, and a smoother or a gradual introduction of externalities is appropriate for developing regions where fossil-fuel burning constitutes the main source of energy.

Region	Scenario	2010	2020	2030	2040	2050
		¢/kWh	¢/kWh	¢/kWh	¢/kWh	¢/kWh
NAME	Local externality	1.7 *(41%)*	1.8 *(25%)*	1.1 *(22%)*	1.3 *(23%)*	1.0 *(19%)*
	Global externality	2.3 *(58%)*	2.7 *(51%)*	1.8 *(45%)*	1.7 *(39%)*	1.7 *(42%)*
OECD	Local externality	1.9 *(38%)*	1.5 *(30%)*	1.3 *(24%)*	1.5 *(26%)*	1.5 *(32%)*
	Global externality	2.7 *(54%)*	2.1 *(60%)*	2.0 *(52%)*	1.0 *(23%)*	2.5 *(77%)*
EEFSU	Local externality	1.6 *(36%)*	1.5 *(24%)*	3.2 *(37%)*	2.2 *(33%)*	0.8 *(16%)*
	Global externality	1.7 *(40%)*	2.5 *(52%)*	4.0 *(72%)*	2.4 *(51%)*	1.7 *(40%)*
ASIA	Local externality	2.6 *(52%)*	6.4 *(54%)*	4.2 *(44%)*	3.8 *(42%)*	1.7 *(28%)*
	Global externality	5.2 *(103%)*	6.7 *(123%)*	4.1 *(77%)*	3.8 *(71%)*	2.2 *(50%)*
LAFM	Local externality	0.4 *(10%)*	0.7 *(14%)*	1.2 *(27%)*	1.1 *(24%)*	1.2 *(21%)*
	Global externality	0.6 *(14%)*	0.8 *(19%)*	1.8 *(57%)*	1.7 *(47%)*	1.3 *(29%)*
WORLD	Local externality	1.6 *(36%)*	2.4 *(51%)*	2.2 *(50%)*	2.0 *(45%)*	1.2 *(30%)*
	Global externality	2.5 *(55%)*	3.0 *(64%)*	2.7 *(62%)*	2.1 *(48%)*	1.9 *(46%)*

Table 24. *Increase in average shadow price of electricity in externality scenarios relative to the Baseline.*

It is stressed, that the results presented in this section are indicative and bear all the uncertainties related to the fuel-prices development, as well as assumed learning parameters of systems with ETL option (e.g., progress ratio, annual growth and declination rates, floor cost; see Table 10). Another policy relevant comment pertinent to the presented values is that the extent of externality charges associated with emission of air pollutants influences significantly the level of cumulative installed capacity of power plants. In other words, the technologies with high external cost are introduced into the system at a lower rate and their investment cost reduction because of ETL is thereby impaired. On the contrary, a reverse effect can occur for technologies with low externality charges: the learning performance of such technologies is accelerated and results in a higher market penetration.

8.2.4.2. Total system cost

The development of the annual total undiscounted system cost in two externality scenarios is presented in Figure 69. As the energy system tries to avoid paying the external costs, presented as striped bars in the graph, new (investment intensive) technologies are being installed and structural changes take place. This leads to a significant increase in total system cost over the computational timeframe relative to the Baseline. The highest contribution of the externality charges to the increase in total system cost, however, occurs in the first period after their introduction, i.e., in 2010. This result confirms again the importance of proper timing of the policy implementation. Lower value of the undiscounted system cost in 2050 in the Global externality scenario compared to the Local externality case is attributed to a larger decrease in power generation resulting from electricity demand reduction and impacts of ETL, as is discussed in Sections 8.2.1.1 and 8.2.1.3.

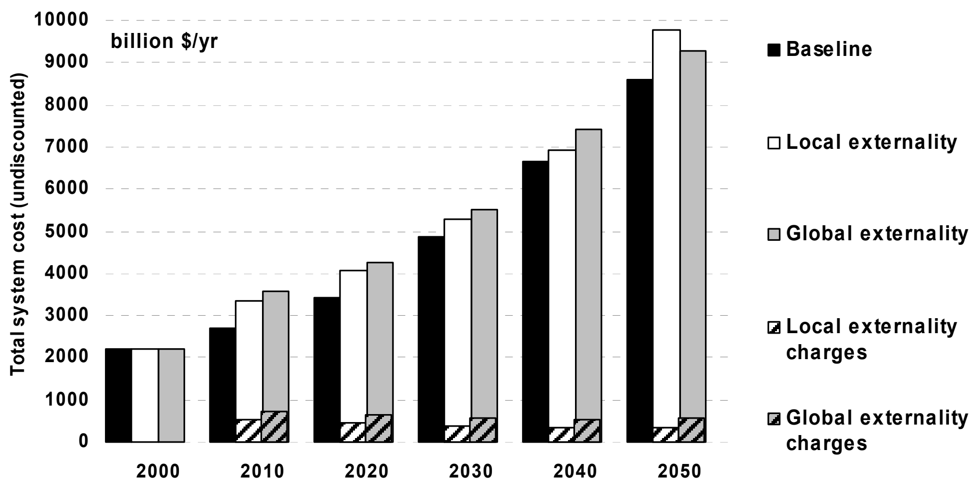

Figure 69. *Development of the total undiscounted system cost under externality scenarios. Striped bars represent the external cost fraction of the total system cost.*

The fraction of undiscounted externality charges in the total cost shrinks in both relative and absolute terms towards the end of horizon, reflecting the capability of the energy system to minimize the extra charges through the structural changes and fuel switching.

Model runs indicate a high relative change in the cumulative total discounted system costs and the welfare loss due to demand reductions, i.e., the objective function used in GMM (Equation 5), because of inclusion of the additional charges in power generation. The total cost increase over the Baseline case for the Local and Global externality scenarios scaled to the population density ammounts to 10% and 13%. As is indicated in Figure 70, the contribution of the external cost itself counts for around 80% of the total cost increase in both externality scenarios. The reminder is attributed to the structural changes and fuel switch occurring within the energy system. Total costs associated to structural changes almost doubles in the Global externality scenario as compared to the Local externality case. This cost increase results from installation of costly power-supply systems such as CO_2-capture and/or nuclear power.

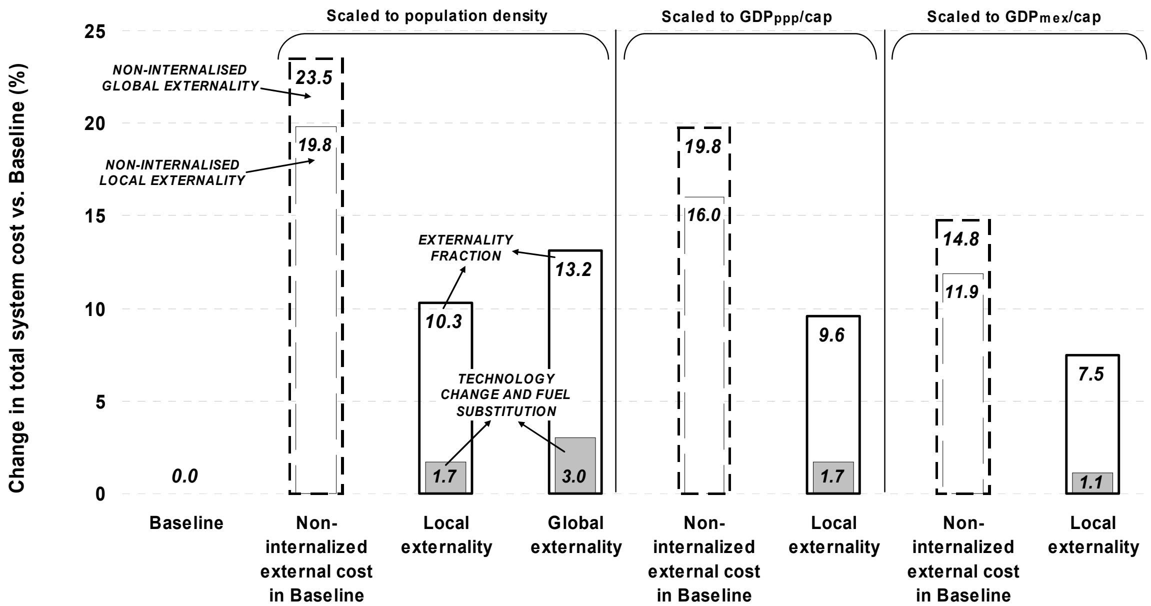

Figure 70. *Change in the cumulative discounted energy system cost for the externality scenarios relative to the Baseline, including external cost fraction.*

Changes in total system cost for the sensitivity scenarios Local externality (GDP_{ppp}) and Local externality (GDP_{mex}) are relatively small, compared to the scenario, where externalities are scaled according to the population density. Reductions in the total discounted externality fraction reflect the downscaling of external costs when considering the income differences among the world regions of GMM. The total cost decrease is more pronounced in the Local externality (GDP_{mex}) scenario, where the overall reduction in costs due to technology shifts by 35% is reported relative to the Local externality case. This result confirms again the observations made in Section 8.2.1.1 and suggests that without a GDP-based scaling the external cost for the developing regions might be overestimated and a lower externality charges can invoke a significant environmental benefits.

Figure 70 also shows a “hypothetical”, non-internalised external cost associated with the Baseline scenario. The non-internalised external cost approximates the cumulative discounted damage cost produced by the electricity sector. This cost is not taken into account in the price of electricity, but is imposed on the society in a form of environmental and health damages. This analysis indicates that the non-internalised externalities might represent up to 24% of the total discounted system cost of the Baseline scenario. On the other hand, the level of energy system cost increase in externality scenarios demonstrates the ability of the energy system to adjust the overall cost well below the environmental damages that occur in the Baseline.

Another observation made here is that the overall damages in the Baseline scenario are dominated by the damages related to air pollution, which creates a considerable potential for ancillary benefits from policies targeted at the CO_2 mitigation. Non-internalised Baseline-damages for the sensitivity scenarios are lower proportionally to the GDP-adjustment used (see Section 8.1.2). Nevertheless, the cumulative damage from the power production in the Baseline scenario, as estimated herein, totals up to 113 trillion \$ for the years 2010-2050, which corresponds to about 3.2% of the cumulative global GDP_{mex} projected for this period by the SRES-B2 scenario.

As summarized in Table 25, these estimates on GDP-losses are comparable to world-wide damages in 2050 quantified by Hirschberg and Burgherr (2003) for a group of selected IPCC scenarios. It is noted that the cumulative damages provided in the aforementioned study, however, have been calculated for a different time horizon and covered the whole energy sector.

Source	**Scenario**	**Damage scaling**	**Cumulative damage (trillions of \$)**		**Cumulative GDP loss (%)**	**GDP loss from air pollution damage (%)**
			Air pollution	**CO_2**		
			2010-2050		***2010-2050***	***2050***
This study	**Baseline**	*Pop.*	93	20	3.2	1.8
		GDP_{ppp}	76	20	2.7	1.5
		GDP_{mex}	55	16	2	1.1
Hirschberg and Burgherr (2003)			***1990-2100***			***2050***
	A1F1	*GDP_{mex}*	1140	130		5.3
	A1T	*GDP_{mex}*	600	65		3.3
	B1	*GDP_{mex}*	250	60		2.2

Table 25. *Cumulative global damages (undiscounted) associated to air pollution and CO_2 emissions in the Baseline and in the selected IPCC scenarios.*

8.3. Summary and concluding remarks

Internalisation of external cost into the price of electricity is an important policy instrument towards achievement of sustainable development in the generation and use of energy. Modelling the impacts of such policies carries certain limitations and uncertainties, among which the most important are issues of valuing socio-political priorities of future energy sector developments, socio-political acceptance of technological options, income distribution effects, discounting of the future damages to the present value, regional differences in valuing externalities, or the rate of policy-induced technological change. Although addressing all these issues were beyond the scope of this analysis, a number of conclusions and insights can be derived from the inclusion of externalities into the power generation system, as analysed using the Global Multi-regional MARKAL model.

Internalisation of externalities with and without global climate change impacts fosters a rapid introduction of emissions control systems and low-emitting power plants. Scenario analysis reveals substantial changes in the electricity production system, i.e., diffusion of advanced technologies and fuel switching. Technology shifts and rapid fuel substitution occur as early as 2010-2020 when external costs are internalized. In the case of the local externalities, the technologies such as coal-fired power plants with emission control, advanced coal power plants, and IGCC replace the conventional coal-fired systems. Natural-gas combined cycle, nuclear power, and renewable-energy technologies increase their share in the power generation mix.

The scenario based on global externalities further accelerates the structural changes in the power production sector. Contribution of the coal-based generation is strongly reduced, and production from the systems with carbon removal accounts for 40% of total electricity generation from coal-fuelled power plants. Natural gas combined cycle systems play a dominant role, and a significant increase in the nuclear energy production is reported. Renewable-energy systems, as well as fuel cells, increase their competitiveness. The GMM model runs indicate some efficiency loss due to the use of scrubbers ($DeNO_x$, $DeSO_x$, and C-capturing), however, the dependency of the electricity sector on the fossil fuels is considerably lower as compared to the Baseline scenario.

Externality charges incurred in power generation increase the price of electricity for the end-users. The reductions in final demand for electricity in industrial and residential & commercial sectors, therefore, occur; electricity consumption is partly substituted by other fossil and non-fossil fuels. Increases in the electricity price especially in the period 2010-2020 suggests that the proper timing of introduction of the policy might be crucial for its acceptability, particularly in regions where fossil-fuels burning constitute the main source of energy. Furthermore, analysis performed with the sensitivity scenarios accounting for regional income-differences in the local externality valuation indicate that a significant improvement in the sustainability performance of the electricity system can be achieved with externality-tax levels that are much lower than levels applicable to most industrialised countries.

The inclusion of external costs in the price of electricity has positive global and local environmental impacts because of the significant emissions reduction. Emissions of SO_2 and NO_x decrease by 64% to 80% in 2030 relative to the Baseline scenario; the rate of elimination of these pollutants then decreases with the rising installation of new fossil-based systems, such as advanced coal, IGCC, NGCC.

The modelling results indicate a strong decarbonisation effect of policies that internalise externalities in the electricity sector. A breakdown of components contributing to the reduction of carbon emissions suggests that the major contributions derive from inter-fossil switch and increase in nuclear and renewable-energy fraction in the primary-energy use. Since the carbon-sequestration technologies become competitive in the Global externality scenario, these technologies appear to present an attractive option in carbon-abatement process.

Significant reduction in CO_2-emissions associated with the Local externality scenario suggests that a considerable ancillary benefits can be invoked by policies that directly address other sustainability issues than CO_2-mitigation.

Increase in the total energy system cost in the externality scenarios associated with structural changes and fuel substitutions induced by internalisation of externalities represent 1.7% and 3% relative to the Baseline scenario. On the other hand, 'learning-by-doing' aids in moderating the level of external cost penalty, which implies policy actions supporting low emitting technologies to follow their learning curves.

The non-internalised damages associated with the reference development of the electricity sector due to air pollution and global warming might be substantial and correspond to about 3% of the cumulative global GDP_{mex} for the years 2010-2050. These damages for the Baseline conditions are largely dominated by those from air pollution alone. Nevertheless, to obtain a more accurate monetary valuation of external damages in different world regions, a detailed "bottom-up" analysis would have to be performed based on the region-specific impact pathway and dose-response functions.

To facilitate further sustainable development in the energy sector via internalisation of externalities, this policy instrument can be improved through appropriate external cost valuation applied not only for electricity, but also for other fossil energy-carriers used in transportation, heating, and industry sectors.

9. Combined policy instruments and synthesis of results

The purpose of this chapter is twofold. One aim is to provide a synthesis of scenario results for selected policy instruments analysed in previous chapters and the second is to evaluate the potential for secondary benefits and synergies associated with the separate or simultaneous adoption of energy-policy domains.

Links between sustainable energy policies occur because they are all applied basically to affect identical human activity: the supply and use of energy. Since the electricity sector is the main focus of this study, an example of coal combustion for power generation is used: replacement of unscrubbed coal-fired power plants by the advanced low-emitting technologies like IGCC and PFBC reduces the direct impacts from air pollution, but at the same time because of high conversion efficiency for these systems the fuel consumption for a unit of output, and hence specific CO_2 emissions, decreases.

When discussing cross-policy interactions, two effects are distinguished. The first refers to **secondary or ancillary benefits** that occur as a positive side effect of implementing a policy to affect sustainability indicators other than those set as an initial priority for the policy instrument applied. The second effect is related to **synergies between policies**, which are defined in this context as an enhanced sustainability performance of the reference energy system as a result of simultaneous implementation of multiple policy instruments. In addition, policies adopted in parallel may involve **trade-offs** among each other, e.g., a welfare loss induced by incremental cost of add-on policies.

Secondary benefits of climate-response policies have been analysed extensively in relation to the expected costs of implementation of the Kyoto protocol in Europe (e.g., Van Vuuren et al., 2005) and with respect to domestic GHG-policies in the US (Burtraw et al., 2003). These studies suggest that the ancillary benefits from invoked reduction in local and regional air pollution can be in the order of 50% of the total cost of climate policy in industrialised regions. Interactions between climate and air pollution policies might be even larger in developing countries, where a reverse accounting can be expected - the GHG-reduction will most likely be considered as a secondary benefit of air quality improvement (Beg et al., 2002).

Alongside environmental and cost co-benefits, a stimulation of technological innovation is expected to emerge from different sustainable policies (Proclim, 2000). Technological progress might be accelerated by addressing different sustainability goals using the same set of technologies. For instance, policy instruments supporting renewable-energy technologies can be applied under a carbon-tax regime, wherein the resources accumulated from the tax revenues would be directly used for learning investments and RD&D. This linkage could stimulate the learning performance of emerging renewable-energy options and enhance their competitiveness. An increased share of renewable systems in the supply mix should eventually lead to a reduced fossil-fuel dependency and lower air-emission rates. Resulting environmental and health benefits may in the long run offset the investment costs needed to introduce these systems within the energy markets.

In what follows, cross-policy interactions are investigated for three policy instruments related to the areas of mitigation of climate change, reduction of air pollution, and the promotion of renewable energy. The following policy instruments are considered: a) CO_2-emissions reduction target in combination with international emissions trading, b) the internalization of external costs due to air pollutants in the electricity price, and c) a renewable portfolio standard in electricity generation. Implications of these policy instruments, which were selected as central cases from the group of scenarios elaborated in Chapters 5, 7 and 8, are first compared separately. Thereafter, combinations of these policy instruments are considered, and the potential for synergies is highlighted.

The remainder of this chapter, which is based on Rafaj et al. (2005b), is organized as follows. Section 9.1 presents the overview of the portfolio of selected policy instruments under examination here and their combinations. Section 9.2 provides the synthesis of selected results in terms of the structural changes in the energy system, energy-related emissions and associated costs. In addition, the results of sensitivity analysis evaluating impacts of the discount rate and the learning rate on the model outcomes are summarised in Section 9.2. Finally, Section 9.3 outlines key conclusions.

9.1. Scenarios

The illustrative portfolio of policy instruments used for the synthesis of modelling results corresponds to three scenarios analysed in detail in previous chapters: **CO_2-cap&trade**, **Renewable portfolio** and **Local externality**. When the three policy elements within this policy portfolio are applied simultaneously or in combination, possible trade-offs and synergies can emerge in terms of cost and environmental impacts. The following combinations of single policy options are examined in a group of **Combined policy scenarios**: CO_2-cap&trade + Renewable portfolio; CO_2-cap&trade + Local externality; Renewable portfolio + Local externality; CO_2-cap&trade + Local externality + Renewable portfolio.

In principle, a large number of scenario permutations are possible. For instance, if the policy elements listed above are applied in combination with different modalities of emissions trading and/or including/excluding ETL, the range of scenarios expands considerably. The selected combinations of policy instruments, as identified in Table 26, however, deal with a majority of key questions and issues related to the impact of individual policy targets and their combinations on the sustainability performance of the global energy system.

SCENARIO	***SPECIFICATION***
Baseline	Baseline case, No-global policy constraint, with ETL, see Chapter 1
Separate policies	
CO_2-cap&trade	Regionalised CO_2 reduction target, Partial equilibrium, Trade of emissions permits, ETL, see Section 5.1.1
Renewable portfolio	Regionalised targets for renewable-electricity share, Partial equilibrium, Trade of green certificates, ETL, see Section 7.1.2
Local externality	External costs from local air pollution internalized in the electricity sector, Partial equilibrium, ETL, see Section 8.1.1
Combined policies	
CO_2-cap&trade + Renewable portfolio	CO_2 reduction target, Trade of emissions permits, Renewable-electricity share target, Trade of green certificates, Partial equilibrium, ETL
CO_2-cap&trade + Local externality	CO_2 reduction target, Trade of emissions permits, External costs from local air pollution, Partial equilibrium, ETL
Renewable portfolio + Local externality	Renewable-electricity share target, Trade of green certificates, External costs from local air pollution, Partial equilibrium, ETL
CO_2-cap&trade + Local externality + Renewable portfolio	CO_2 reduction target, Trade of emissions permits, Renewable-electricity share target, Trade of green certificates, External costs from local air pollution, Partial equilibrium, ETL

Table 26. *Naming and description of the combined-policy scenarios.*

9.2. Scenario Results

In this section, a synthesis of the results is provided, and implications emerging from the set of three central policy-driven scenarios are first compared for separate policy implementation, with an emphasis placed on structural changes in the power-generation mix, primary-energy consumption, environmental impacts as well as related costs incurred when meeting sustainability goals. For scenarios where policies are applied in combination or complementarily, potential cross-policy synergies and trade-offs are indicated.

9.2.1. Structural changes

9.2.1.1. Electricity generation

Electricity generation is characterised by a vigorous growth in the Baseline scenario with the bulk of this growth being driven by developing regions. Coal-fired power plants dominate the electricity market, with increasing market shares occurring for advanced technologies (PFBC, IGCC). The gas combined cycle, as well as wind turbines, experience significant growth. The contribution from nuclear power does not grow substantially, but a substitution of conventional plants by new reactor designs takes place. The amount of hydroelectric production grows only slightly.

All policies imposed on the Reference Energy System (RES) reduce the overall power generation, since the production costs of electricity increase. The largest decrease in electricity production in 2050 relative to the Baseline is observed in the Renewable portfolio case (-5.6%), while internalising externalities from air pollutants reduces total power generation to a smaller amount (-3.6%). This result is an indication of the severity of the policy options analysed herein and suggests that, under conditions of forced market share of electricity generated from renewable-energy sources, the induced increase in electricity price results in electricity demand reductions and substitution of electricity for other fuels by the end-users.

For the CO_2-cap&trade scenario, the CO_2-emissions reduction target is primarily achieved by a strong reduction (-48% compared to the Baseline scenario) of coal combustion for power production, as is shown in Figure 71. The only coal-based technology that undergoes significant increase compared to the Baseline scenario is the IGCC with carbon capture and sequestration. Generation systems based on NGCC become the main source of electricity by the end of the time horizon, followed by nuclear power. Natural gas and nuclear power together account for one half of the total electricity production in 2050. Renewable electricity sources increase their contribution by 21% as compared to the Baseline scenario.

The renewable portfolio policy forces the 35% share of renewable electricity to be achieved by 2050. Electricity generation from fossil-fuelled technologies is steadily reduced over the computational time frame. Both coal- and gas-based generation are affected, and the total contribution of the fossil sources in 2050 is lowered by 25% relative to the Baseline scenario. The role of nuclear energy in the electricity market is also reduced, especially in the last time period.

Internalising the local externalities into the electricity price changes the structure of the power generation mix immediately after the policy implementation. Coal remains the major fuel for power production; though, its share is halved already in 2030 relative to the Baseline case and the conventional pulverised coal plants are replaced by advanced systems with SO_2 and NO_x emissions control, e.g., PFBC and IGCC. NGCC and other natural gas based systems increase their share in power production to a level of 37% and 25% of the total electricity supply in 2030 and 2050. Finally, the share of renewable energy and nuclear plants in 2050 is increased by 28 % relative to the Baseline scenario because of lower external costs charged to these systems.

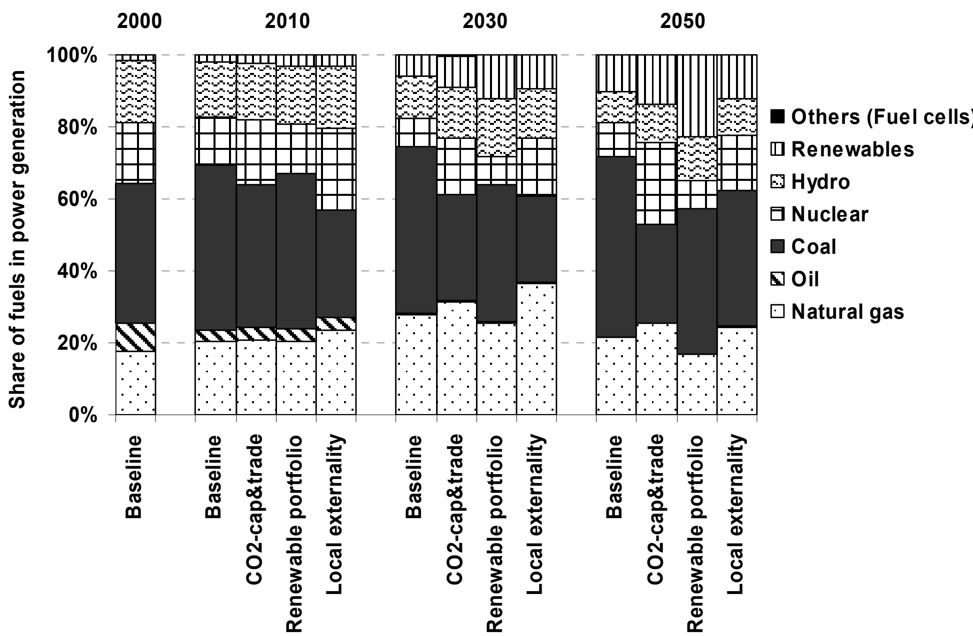

Figure 71. *Development in global electricity production by fuel under the Baseline and policy scenarios (relative shares).*

Linkages between policy instruments are exemplified by plotting the changes in renewable electricity production over the Baseline scenario, as is shown in Figure 72. Growth in renewable power generation under the Renewable portfolio scenario is forced by the policy-constraint. On the other hand, production increases in the CO_2-cap&trade and Local externality scenarios are invoked by the zero emission rates associated with exploitation of renewable energy sources. A synergetic effect is reported for the scenario combining CO_2-constraint with internalisation of local external cost, where the total renewable-based electricity production is higher (mainly resulting from more hydro-power generation) than in the separate implementation of both policies.

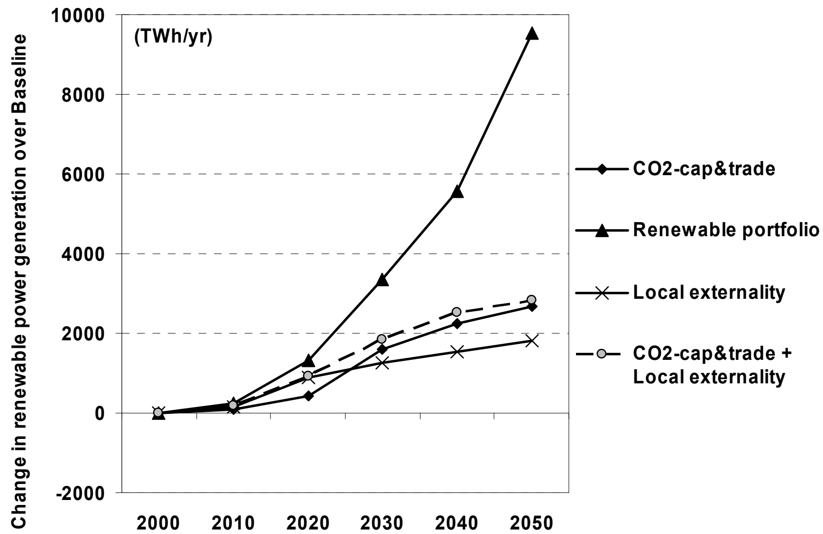

Figure 72. *Change in the global renewable power generation for policy scenarios over the Baseline.*

Differences in impacts from policies are illustrated further in Figure 73, which shows the power-generation profile in 2050 for the Baseline and the three single-policy scenarios being considered. In the CO_2-cap&trade scenario, the coal-based generation is displaced in favour of natural-gas (NGCC) power generation, renewables (including hydropower) and, above all, nuclear power plants. Advanced coal-based technologies with CO_2 capture, however, penetrate the market at a significant level.

Targets prescribed under the Renewable portfolio scheme are achieved by a significant increase in electricity generation from biomass, hydropower, geothermal sources, as well as from solar photovoltaic systems (SPV). Growth in generation from wind turbines is not substantial, since this technology is already approaching its technical potential in the Baseline. The Renewable portfolio scenario is the only one where the SPVs gain a market share in 2050. Increases in renewable electricity generation are balanced by reductions in generation from NGCC, coal plants, and advanced nuclear systems.

The main impact of the internalisation of external costs on the power sector is the massive elimination of generation from conventional coal-fired power plants, and the accelerated market penetration of advanced coal systems with low SO_2/NO_x emissions rates. Similarly, the low emission factors for air pollutants associated with NGCC systems explain the growth in production from this technology. Additionally, low external costs increase competitiveness of nuclear power plants and renewables as compared to the Baseline scenario.

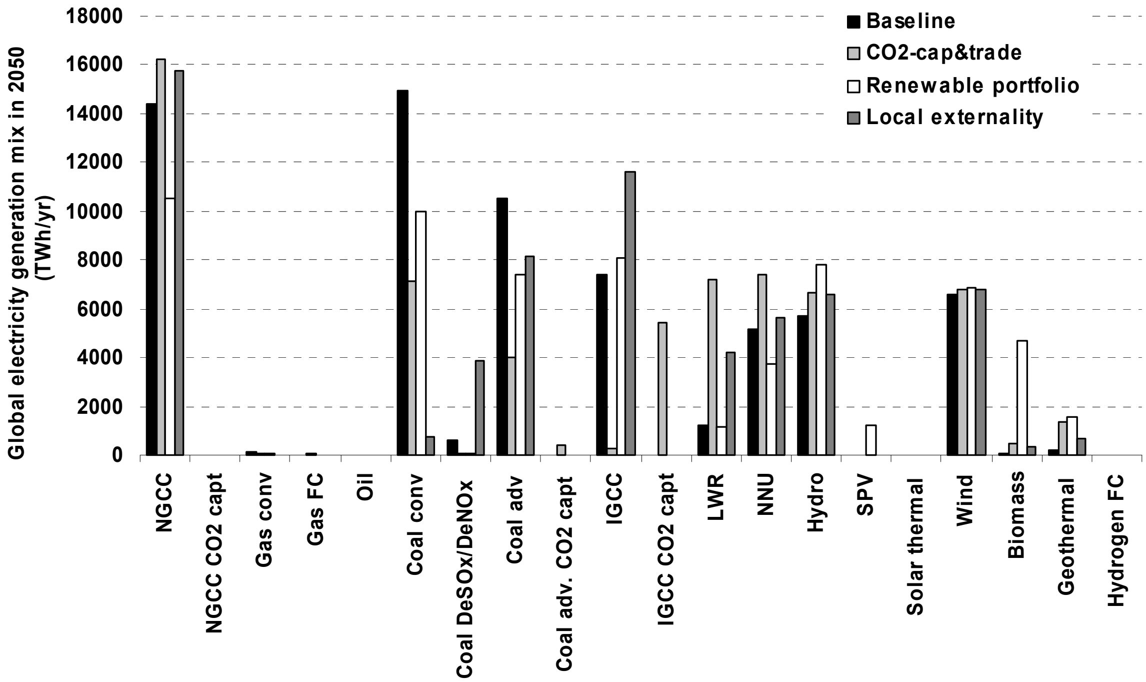

Figure 73. *Contribution of technologies to the global electricity generation mix in 2050 in the Baseline and policy scenarios. For nomenclature, see Table 8.*

Findings from this study summarized here suggest that nuclear power, NGCC, and the advanced coal technologies with SO_2/NO_x control, operated in combination with fossil-fuelled plants with carbon-removal, constitute an attractive technological mix towards carbon and air pollution mitigation strategies for the time horizon investigated.

9.2.1.2. The role of nuclear energy in the sustainable energy policies

Although not analysed in detail earlier, the set of policy scenarios provides insights into the long-term role that nuclear power could play in achieving the sustainability of the global energy system. Clearly, utilization of nuclear energy is and will be an important component of the portfolio of carbon mitigation strategies, as well as in strategies aimed at the abatement of air pollution. Moreover, the contribution of nuclear energy influences substantially the ways in which the power sector reacts to the policies imposed.

Nuclear power presently provides about 17% of world-wide electricity, and this share is projected to decrease to 10% by 2050 in the Baseline scenario, in spite of capital cost reductions of advanced nuclear reactors anticipated through the LBD impact. As shown in Figure 74, the highest increase over the Baseline in the nuclear-based power production is reported for the CO_2-cap&trade scenario. The stringent carbon constraint results in nuclear-power penetration that is by factor of 2.3 higher than in the Baseline case by the end of the computational time frame. The fraction of nuclear electricity in the global generation mix rises to 23% in the CO_2-cap&trade scenario in 2050, which represents a 35% increase over the current market share. The bulk of increased nuclear-power production is attributed to the advanced nuclear systems that gradually replace conventional reactors.

The overall increase in nuclear power generation with respect to the Baseline scenario is less pronounced in the Local externality scenario. In this case, a growth by 53% is projected for the end of horizon. On the other hand, the contribution of nuclear power in 2050 is less by 23% in the Renewable portfolio case relative to the Baseline levels, with this decrease occurring mainly because of decelerated learning effect for advanced nuclear systems.

In current nuclear plants, 22 tonnes of uranium are typically needed to generate 1 TWh of electricity. The cumulative nuclear-based electricity generation in 2000-2050 for the CO_2-cap&trade scenario corresponds to 415'000 TWh, which means that about 9.1 million tones of uranium are required. Reasonably assured uranium reserves recoverable at less than 130$/kgUranium are reported in UNDP (2000) to be about 3.2 million tones. Additional uranium resources at extraction costs at less than 260$/kgUranium are estimated to be 5.1 million tonnes. Finally, speculative resources (i.e., without cost specification) might add about 12.1 million tonnes. The implication of these estimates is that the substantial increase in utilization of nuclear energy using current technology would require an exploitation of resources of fissile materials in the cost categories above 260$/tU, while some of these resources are at the moment only speculative and have yet to be discovered.

Another implication and the real concern for the large-scale utilisation of nuclear energy is the cost and feasibility of the disposal of spent nuclear fuel and radioactive wastes containing long lived isotopes. Table 27 provides rough estimates of the amount of spent fuel that would be produced under the levels of nuclear power generation projected for the Baseline, and for the scenarios CO_2-cap&trade and Local externality. In addition, amounts of plutonium and minor actinides contained in the spent fuel are indicated for respective scenarios based on U.S. DOE (2004) and Dones (2003). Reprocessing of spent fuel to recover Pu-239 for the MOX-fuel production is not assumed in the calculations presented herein.

Cumulative production 2000-2050 (t)	Baseline	CO_2-cap&trade	Local externality
Spent fuel	772’000	1’520’000	1’235’000
Plutonium	7’700	15’200	12’400
Actinides	950	1’870	1’520

Table 27. *Estimates of cumulative production of nuclear spent fuel and other radioactive materials for the Baseline and policy scenarios.*

To avoid the potential threats of costly uranium supplies and the high costs of waste disposal, which may drive a closing of the fuel cycle, additional technology improvements are probably needed in terms of improved fuel burn-up rates in advanced reactors, implementation of plutonium/minor-actinide recycle to mitigate the waste-disposal problem, development of thorium reactors, or (eventually) a larger utilization of breeder reactors (to address both the resource and the waste problems). If the development of an improved nuclear fuel cycle performance does not take place, the results reported above might be unrealistic, since the high fuel-cycle costs of both reduced uranium resources , reprocessing (if required), and waste disposal will deteriorate the future competitiveness of nuclear energy. Unfortunately, the present version of GMM does not allow examination of the alternative nuclear fuel cycles.

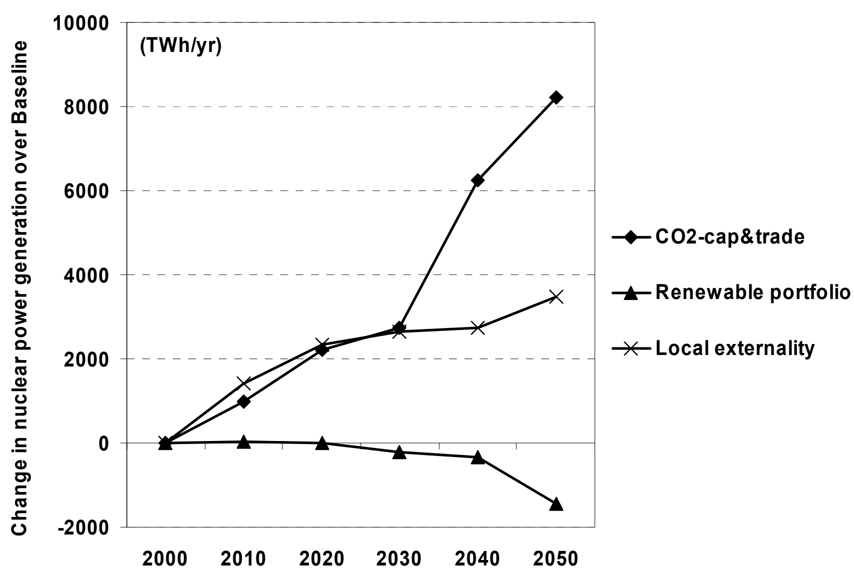

Figure 74. *Change in the global nuclear power generation with respect to the Baseline under policy scenarios.*

Under the carbon-mitigation regime, the installation of new nuclear capacities is substantially accelerated, since nuclear energy plays an important role in the carbon abatement. Increased nuclear-power production is further enforced by endogenous learning effects for advanced reactors. Figure 75 depicts the time dependency of regionally distributed additions in the nuclear generation capacity over the Baseline for the CO_2-cap&trade scenario and for the Local externality scenario. In the first case, the largest increment in the nuclear capacity between 2010-2040 is reported for the NAME region. In 2050, the capacity additions are distributed almost equally among industrialised regions and ASIA. Nuclear capacity increases in LAFM appear at a substantially smaller extent, suggesting that other CO_2-mitigation options (e.g., fuel switching, CO_2-capture, renewables or demand cuts) prevail in this region.

In the Local externality scenario, the majority of the capacity additions originates in the NAME and OOECD regions between 2010-2030, followed by the ASIA and EEFSU region. Because of a rapid elimination of coal-fired systems, the total capacity growth in 2010 and 2020 is even greater than in the CO_2-cap&trade scenario. Total nuclear capacity increases in the second half of the computation period are dominated by the additions in ASIA.

The growth in nuclear-power capacity reported for the CO_2-cap&trade scenario is approaching the market penetration limits specified by annual maximum growth-rate of 13%/yr for advanced and 4%/yr for conventional plants. The total new nuclear-capacity installations under the CO_2-cap&trade scenario within the period 2010-2050 represent nearly 2.5 TW_{el} on the global level. This installation rate would mean on the average a construction of around 52 new units (of 1.2 GW capacity each) per year, between 2010-2050, i.e., about 1 new reactor every week somewhere in the world[12]. It must be remembered that the life-time extension of operating plants to 50-60 years would reduce this huge capacity additions by around a factor of two.

[12] For comparison, the nuclear capacity construction rate during the early 1970s was rapid, averaging 30% capacity expansion per annum from 1970 to 1975 worldwide (McDonald, 2004). Past experiences in the capacity growth for the same period in the US show the average additions of about 10 reactor units per year. In 1974, which was the most active year in the US, 13 reactors were added to the grid.

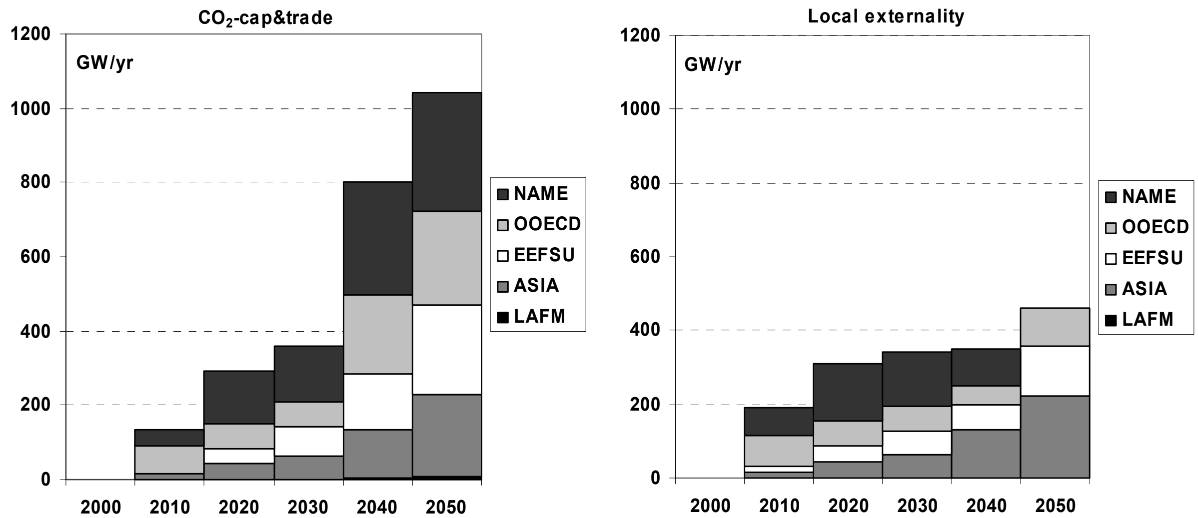

Figure 75. *Regional distribution of the additional nuclear electricity generation capacities relative to the Baseline.*

9.2.1.3. Primary energy consumption

Changes in the primary energy supply are strongly determined by the technological shifts in the electricity sector. While global primary energy consumption in the Baseline scenario is largely dominated by fossil energy carriers, a significant increase in non-fossil sources is observed in the CO_2-cap&trade scenario. Contribution of nuclear energy doubles, and renewables increase their share by 25% by 2050 over the Baseline scenario, as is indicated by Figure 76. By the end of the time horizon consumption of coal is reduced by 50% when compared to the reference case. Natural-gas consumption remains at the same level, and reductions in oil usage occur at a lower level.

In the case of the Renewable portfolio scheme imposed on the Baseline scenario, the contribution of renewables reaches more than 25% of the global primary energy consumption in 2050. Renewables substitute for other primary energy fuels, particularly for coal and nuclear energy, where reduction by 20% and 23% relative to the Baseline is observed. Internalisation of external costs from air pollution in the power sector leads again to a strong reduction in coal consumption, but this reduction is substantially larger during the period 2010-2030 in comparison to other policy scenarios. Coal is replaced primarily by nuclear energy, and the rapid reduction in coal use is balanced with rising use of natural gas, oil and renewable power.

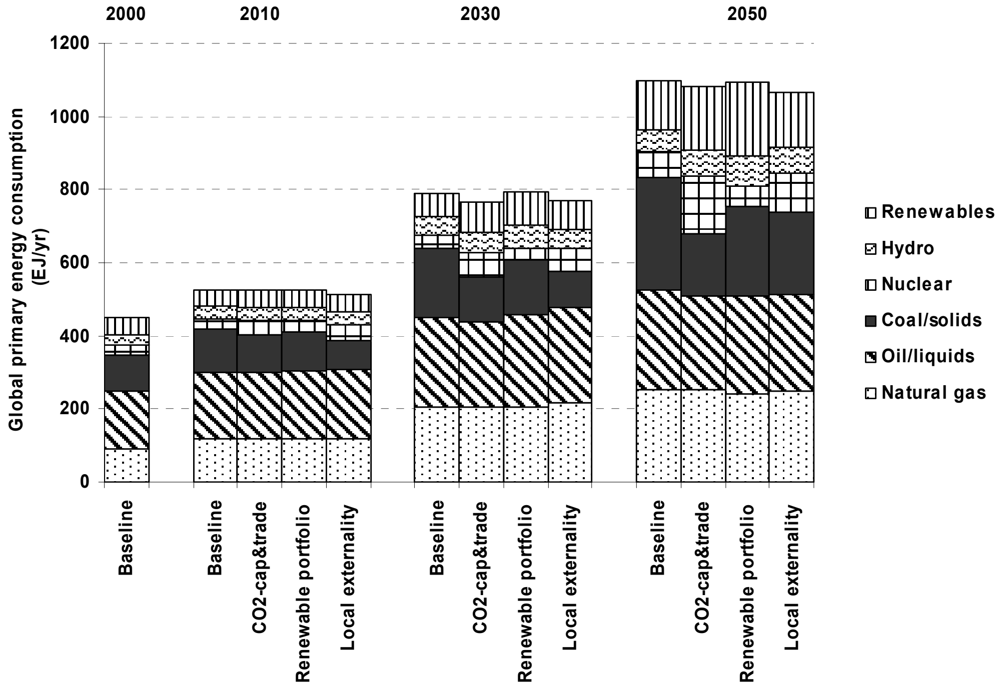

Figure 76. *Time evolution of global primary energy consumption by fuel under the Baseline and policy scenarios.*

9.2.2. Environmental impacts

9.2.2.1. Global CO_2 emissions

A common effect of the three policy instruments under examination here is the reduction of CO_2 emissions as compared to the development in the Baseline. The extent of the policy-induced carbon mitigation depends on the particular policy tool being implemented, on the deployment of the carbon-control technologies (e.g., renewable energy or nuclear energy versus CO_2-capture), and on the timing and effectiveness of the respective policy implementation in different world regions. Furthermore, various cross-policy interactions contribute to the decarbonisation effects of policies adopted concurrently.

Under the CO_2-cap&trade scenario, emission growth is the strongest around 2020, while a stabilisation trajectory begins after 2030 to reach the level below 10 GtC/yr by 2050. Global carbon emissions decrease over the Baseline scenario by 41% in 2050 and represent an absolute reduction of 6.9 GtC/yr. On the basis of the relative CO_2 emissions summarized in Figure 77, the strongest carbon-emission decrease for the CO_2-cap&trade policy element occurs after the year 2020, when all regions have an obligation to reduce their CO_2 emissions. On the other hand, the most significant reductions for the Local externality scenario are achieved between 2010 and 2020, and the reduction goes actually beyond the targets of the

CO_2-cap&trade scenario. This early reduction of CO_2 emissions results from the substantial fallback of coal-based power generation implicit to the premature retirement of coal plants without SO_2/NO_x control. By the end of the time horizon, the Renewable portfolio and the Local externality scenarios show similar reductions in carbon emissions, with annual reductions in 2050 over the Baseline scenario of 10.3% for the former and of 13% for the latter scenario.

Finally, the CO_2-reduction trajectory for the scenario where carbon constraint and local external costs are applied in parallel (i.e., the scenario CO_2-cap&trade + Local externality) documents that in the case of Combined policy scenarios, ancillary benefits and synergies can be expected from policies elements that directly address different sustainability issues: CO_2 mitigation and air pollution reduction. This phenomenon of the so-called double environmental dividend has been reported in similar studies (Hourcade et al., 2001) and is related not only to carbon emissions, but also to emissions of CH_4, SO_2 and NO_x.

Another synergetic effect is observed in the scenario Renewable portfolio + Local externality, where the carbon emission decrease is larger in 2040 and 2050 as compared to the single policy cases. Two reasons for this result can be identified: a) the Renewable portfolio forces a greater penetration of carbon-free supplies based on renewable-energy sources than is achieved by internalising the air-pollution damages, and b) the low local external cost of nuclear plants increases its competitiveness, and, thereby, the contribution of nuclear power is higher than in the separate adoption of the Renewable portfolio.

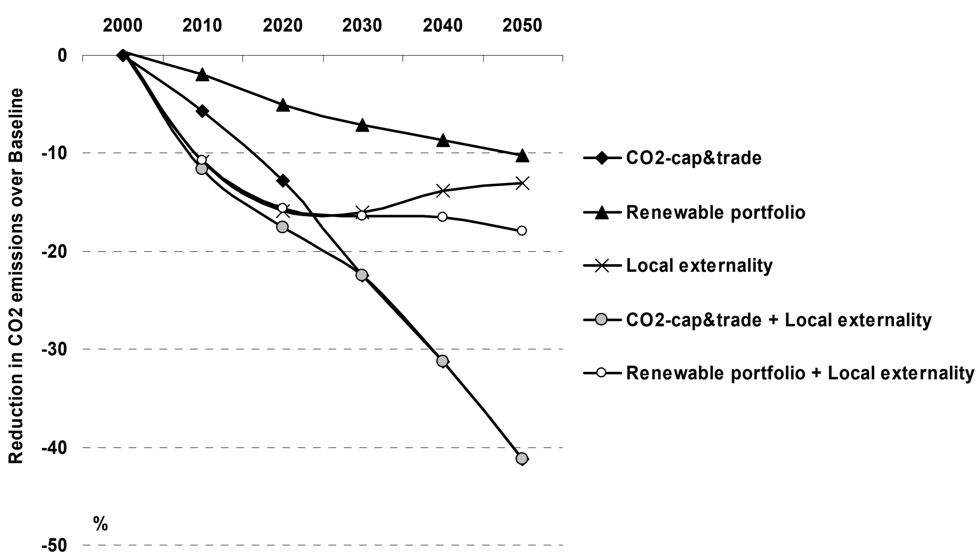

Figure 77. *Change in global carbon emissions relative to the Baseline scenario for single and combined policy scenarios.*

9.2.2.2. Emissions of air pollutants

Secondary benefits and synergies inherent to the separate or combined implementation of sustainable polices are documented in Figure 78 showing the reductions in SO_2 and NO_x emissions from the electricity sector with respect to the Baseline scenario. Among the single-policy cases, the largest reductions in both aforementioned emittants are projected for the Local externality scenario, which explicitly accounts for damages related to air pollution. The emission reducing effect of internalisation of externalities is enforced when the Local externality scenario is coupled with renewable-energy and carbon-policy targets.

Synergies between policies applied simultaneously are most pronounced in the period 2040-2050 for the scenario CO_2-cap&trade + Local externality. Trade-offs are attributed to the composition and quantity of the cumulative coal-based power generation in the end of the time horizon that is in total by 30% lower in the CO_2-cap&trade scenario, as compared to the Local externality case, but at the same time the external cost applied lead to a larger elimination of unscrubbed pulverised coal systems (see also Figure 73).

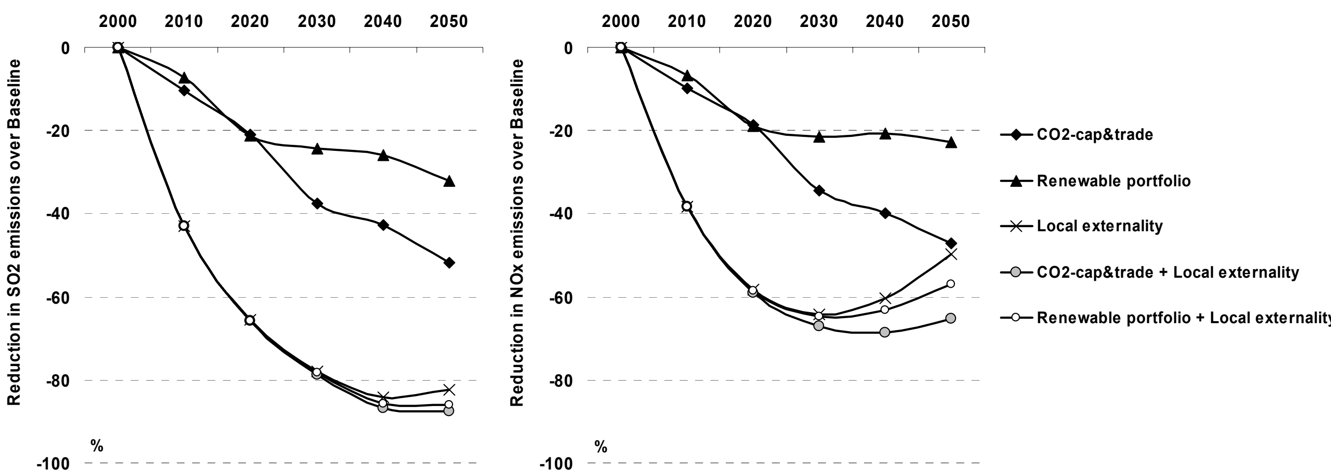

Figure 78. *Change in the global SO_2 and NO_x emissions from the electricity sector in the policy scenarios relative to the Baseline.*

Particularly important from the policy-making viewpoint are the secondary benefits of the separate application of the climate-policies, herewith represented by the CO_2-cap&trade scenario. The modelling results indicate the reduction in SO_2 and NO_x emissions in 2050 invoked by the long-term carbon constraint to be in the order of 52% and 47%, respectively. Environmental and health ancillary benefits are thereby proportional to the avoided damages due to local and transboundary air pollution. This finding may have an important policy implication because it implies that secondary benefits could help to outweigh the direct cost of CO_2 mitigation. Secondary gains can be large especially in urban areas of developing regions with poor air quality standards and should be considered by policy makers (Beg et al., 2002).

9.2.3. Global indicators

Figure 79 shows how the carbon reduction associated with different energy-policy options is attained by plotting baseline-normalized carbon intensity (i.e., CO_2 emitted per unit of primary energy consumed) versus primary energy intensity (i.e., primary energy consumed per unit of GDP produced), all expressed as a function of time. Although all scenarios are inclined to achieve the CO_2 emission decreases by reducing the carbon intensity, projections of how the global reference energy system reacts to meet respective policy goals, however, vary somewhat across scenarios. The strong decarbonisation effect of the CO_2-cap&trade scenario results in a relative decrease in carbon intensity by 40% relative to the Baseline, which makes the CO_2-cap&trade policy scenario the least carbon intensive, followed by the Local externality scenario. In the CO_2-cap&trade scenario the reduction in energy intensity grows between 2020-2030 and becomes lower towards the end of time horizon, while the decrease in energy intensity is most pronounced under conditions of the Local externality scenario, where the external-cost charges lead to the strongest demand reduction especially for periods 2010-2020.

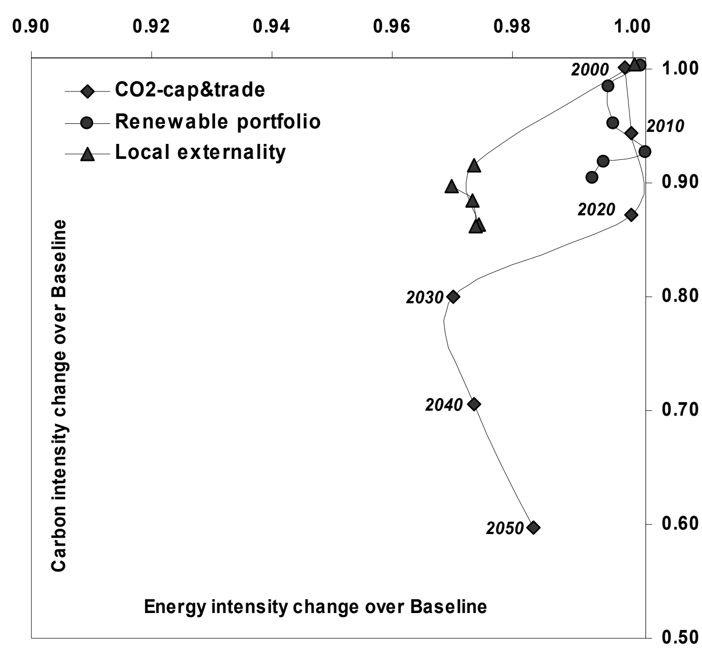

Figure 79. *Projection of changes in energy and carbon intensity relative to the Baseline for selected policy scenarios. (Index: Baseline = 1)*

9.2.4. Cost impacts

9.2.4.1. Carbon permit price

The policy options analysed in this study suggest varying potentials to reduce carbon emissions at different cost levels. Marginal carbon abatement costs (equal to carbon emission permit prices) are presented in Figure 80 for the CO_2-cap&trade scenario and three Combined-policy scenarios, where explicit CO_2 reduction targets apply. Carbon-permit prices vary across scenarios and over time. Differences are determined by: a) the level of the severity of the carbon constraint relative to the Baseline case in combination with other policy elements; b) the dynamics of technology change (ETL); and c) the CO_2-permits trade specification.

In all scenarios, the price of carbon permits increases over the time horizon, with the exception of the period around 2020. The reduction in marginal cost in this period is explained by the increased supply of carbon permits originated from Non-Annex-B countries joining the carbon-mitigation regime from 2020 onward. In 2050, the carbon-permit price reaches 145 \$/tC. This price is reduced by 23% when the CO_2-emission caps are combined with the Renewable portfolio policy instrument.

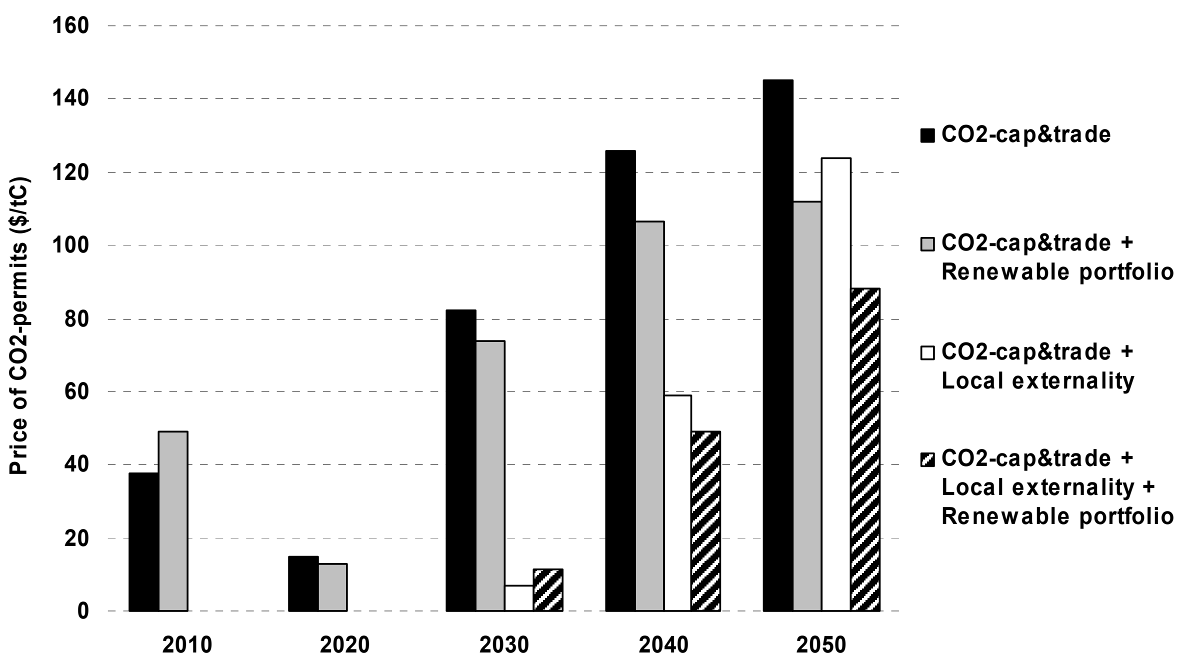

Figure 80. *Marginal cost of CO_2-emission permits for scenarios combining CO_2 reduction with other sustainability objectives.*

Similarly, the carbon-permit price is lower under the scenario that combines the carbon-reduction constraint with the inclusion of external costs associated with air pollution. In addition, the externality-induced rapid elimination of coal-fired conventional power technologies during the period 2010-2020 reduces the CO_2 emission level beyond the target specified by CO_2-cap&trade scenario, which results in zero carbon-permit prices in the periods 2010 and 2020.

The price reducing effects of combining selected policy elements are made more pronounced for the scenario where the three policy instruments are applied simultaneously (CO_2-cap&trade + Local externality + Renewable portfolio).

The significant marginal cost reduction in 2040-2050 is attributed to ETL, since the combination of policy elements accelerates the learning performance of carbon-free (or low-carbon) electricity generation technologies (e.g., advanced nuclear plants, renewables, IGCC with carbon capture).

9.2.4.2. Green certificates price

Observations similar to the marginal cost of carbon permits apply for the price of green certificates, which is equal to the marginal cost (or the shadow price) of renewable electricity constraint defined by the Renewable portfolio standard, as is discussed in Section 7.1.2 (see Table 15).

The marginal cost varies in the case of sole policy-adoption over the time horizon within a range from 2.6 ¢/kWh to 5.2 ¢/kWh (Figure 81). An important finding is that the increased supply of green certificates available for trade in 2020, which is the period where the regions with large renewable-energy potentials - ASIA and LAFM – begin to implement the policy target, results in price reduction in years 2020-2030, as compared to 2010. The lowest cost reported for the period 2030 reflects also the ability of the power sector to adjust its structure to the renewable policy constraint.

When the Renewable portfolio scheme is combined with the external-cost policies (i.e., the Renewable portfolio + Local externality scenario) and with a carbon constraint (i.e., the Renewable portfolio + Local externality + CO_2-cap&trade scenario), the fraction of renewable electricity generated in 2010-2020 exceeds the fractional target prescribed under the single-policy conditions as is shown in Figure 71. The marginal costs for this time segment, therefore, are zero.

Decreases in the price of green certificates reported for the Combined-policy scenarios in the period 2040-2050, relative to the separate renewable-policy implementation, is again a consequence of LBD cost-reducing effects. Moreover, larger electricity-demand reductions in the Combined-policy scenarios result in a lower electricity production from renewables in absolute terms, although the fractional target prescribed by the Renewable portfolio policy remains the same.

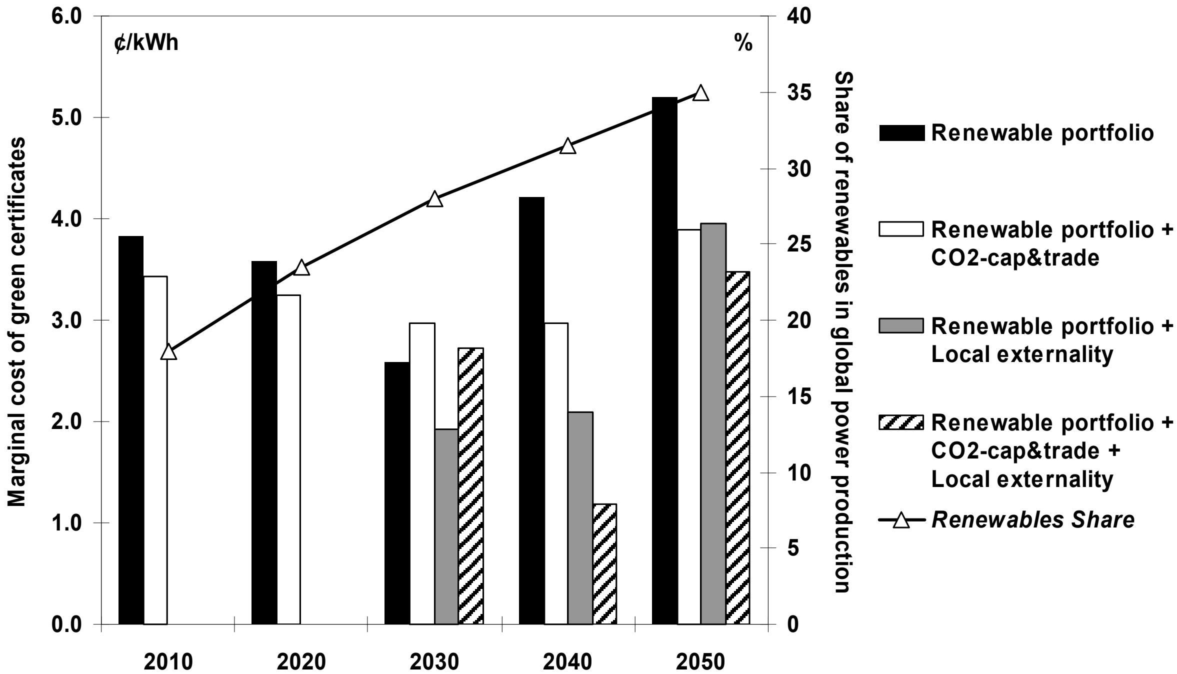

Figure 81. *Marginal cost of green electricity certificates for selected scenarios combining the Renewable portfolio standard with other sustainability objectives.*

9.2.4.3. Total system cost

Figure 82 displays the relative changes of the total discounted energy system costs and the welfare loss due to demand reductions (i.e., the objective function used in GMM) for the policy options analysed as compared to the Baseline scenario. Variations in the value of the objective function reflect the level of cost effectiveness of the respective policy instrument and the severity of constraints imposed. The discounted energy system cost together with the welfare loss (the sum of consumers and producers surpluses) is increased by 1.6% under the CO_2-cap&trade scenario, where the carbon-mitigation constraint is applied on the entire energy system. The Renewable portfolio standard, as formulated in this study, emerges as the least-cost single-policy option (1.2% increase in total cost relative to the Baseline), which is explained by the fact that the constraint is affecting mainly the electricity sector alone. The

Local externality scenario is the most expensive of single-policy elements primarily because of premature closure of existing conventional coal-fuelled power plants and the costs associated with the rapid technology shifts and inter-fossil fuel switching in periods 2010-2020.

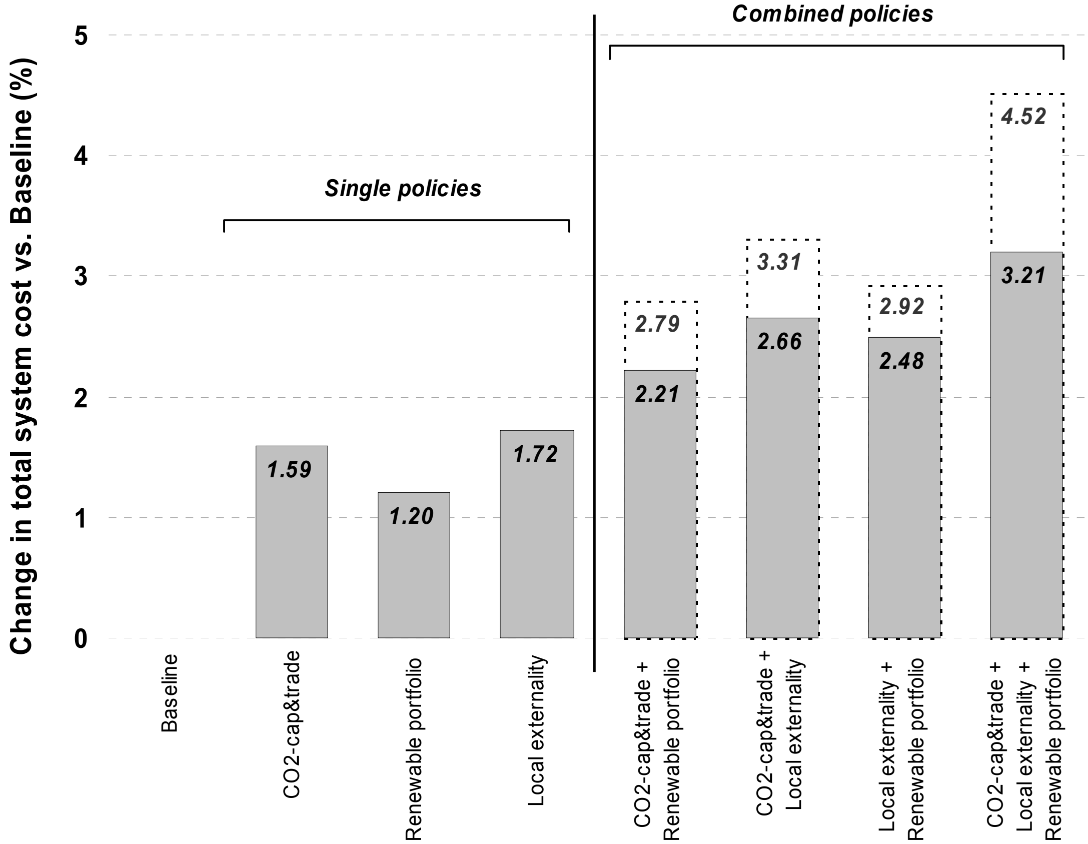

Figure 82. *Change in the cumulative discounted energy system cost relative to the Baseline scenario (excluding charges related to taxes or external cost). Dotted bars represent the sum of relative increases in total costs for single-policy scenarios.*

Potential trade-offs and synergies resulting from the simultaneous application of policy options become again relevant, when the increase in the total discounted energy system cost and the welfare losses for the separate implementation of policy elements are added together and compared with the modelling results from the Combined-policy scenarios. The increase in the objective function for the set of combined policies is by 15 to 30% lower than the sum of increases in three single-policy scenarios considered in this study. This finding illustrates the existence of synergies between the policy instruments considered here and suggests that a double dividend associated with pursuing different sustainability objectives can be considerably large. Hourcade et al. (2001) indicates the aggregate cost savings by 40% resulting from simultaneous reduction of CO_2 and SO_2 emissions, especially for the Asia region, but this effect can occur only if sufficient resources will be transferred inter-regionally through, for example, the Kyoto-like flexible mechanisms.

Increases in the total system cost depicted in the figure above represent only the direct cost associated with the implementation of the set of policy instruments. Nevertheless, this indicator for policy cost is incomplete because a number of (unaccounted) secondary benefits occur by the separate or complementary adoption of sustainable policies in terms of significant reduction in air pollutants, as discussed in Section 9.2.2.2.

Secondary benefits of policy options can be quantified by estimation of avoided damages due to adverse impacts of local and regional air pollution. Using the assumptions on unit damage cost per tonne of SO_2, NO_x and PM applied in Chapter 8 for calculation of externalities from the electricity sector, the avoided damage cost related to the set of policies under examination herein have been compared with the respective changes in total system cost. As summarised in Figure 83, the cumulative avoided damages from the electricity sector, adjusted to the regional differences in GDP_{ppp} per capita (see Section 8.1.2), overweigh in all cases the increases in total energy system cost induced by the policy adoption. Secondary gains of the combined policy scenarios CO_2-cap&trade + Local externality and CO_2-cap&trade + Renewable portfolio are enhanced further by the ancillary co-benefits invoked from the synergetic effect of the joint policy adoption.

Implications of this result are highly relevant for policy-making efforts in the area of climate change, particularly for the developing counties, since they suggest that the secondary benefits of the CO_2-abatement are offsetting the direct costs of mitigation. However, Figure 83 also indicates a large uncertainty in the quantification of secondary benefits attributed to the different method of scaling the avoided damage. The lower range of avoided damages in the figure represents the damage cost adjusted to the population density, and the upper range reflects the damage cost scaled to GDP_{mex}. An extensive review of analyses of secondary benefits from climate response policies provided by IPCC (2001a) shows large differences in the estimates of net ancillary benefits ranging from a marginal share of the policy costs to more than offsetting them. The main sources of uncertainty have been identified as follows: a) an absence of standardised methodology for the estimation of secondary benefits; b) the monetisation of VLYL in different regions, and c) the definition of the baseline. Therefore, the estimates of secondary benefits reported in this section should be considered as indicative results surrounded by uncertainties due to a number of factors that require a more complex evaluation.

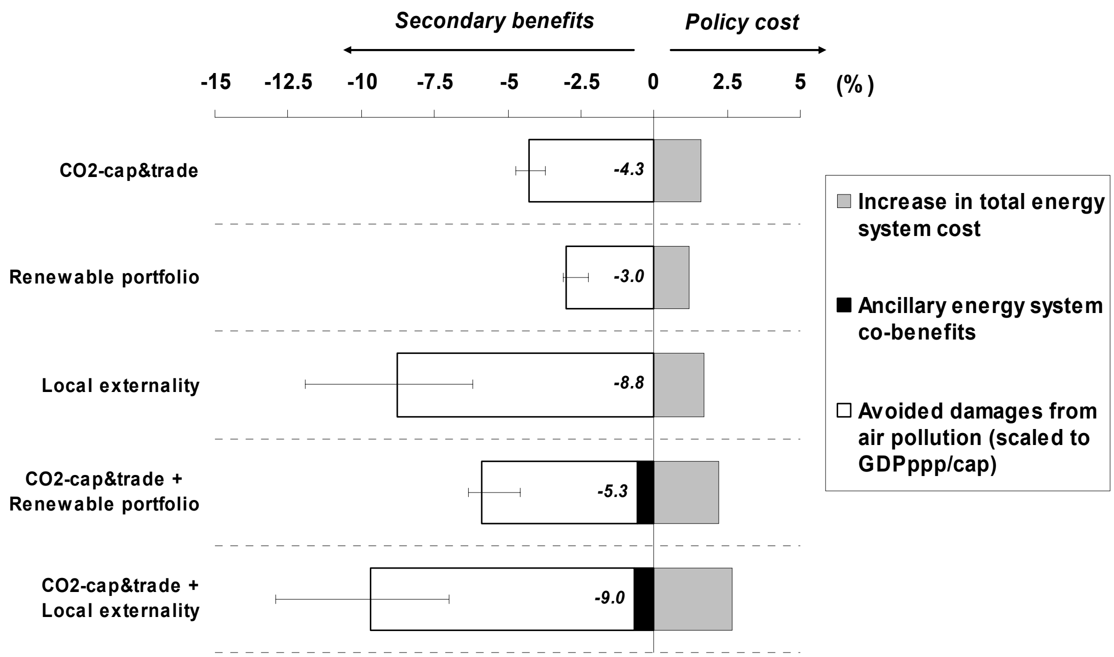

Figure 83. *Comparison of cost and secondary benefits for selected single- and combined-policy scenarios expressed as change in the cumulative discounted energy system cost relative to the Baseline scenario (excluding charges related to taxes or external cost).*

9.2.4.4. Average policy cost

The cost effectiveness of the portfolio of policy instruments analysed in previous chapters is evaluated further by using the average cost (*AC*) of a policy instrument in relation to the sustainability performance of RES, measured by three indicators: a) CO_2 abatement, b) SO_2 emission reduction, and c) incremental electricity generation from renewable energy sources, while these indicators are compared to the Baseline scenario. For the calculation of the average policy-cost, the following formulas apply:

$$AC_{avoided\_CO_2} = \frac{\Delta CUMC_{(2000-2050)}}{\Delta CUM\_CO2_{(2000-2050)}}; \; AC_{avoided\_SO_2} = \frac{\Delta CUMC_{(2000-2050)}}{\Delta CUM\_SO2_{(2000-2050)}};$$

$$AC_{added\_ren} = \frac{\Delta CUMC_{(2000-2050)}}{\Delta CUM\_ren_{(2000-2050)}}, \tag{28}$$

where *ΔCUMC* is the difference in cumulative undiscounted energy-system cost between the Baseline and a given policy scenario. The denominator *ΔCUM_[CO2,SO2,ren]* used in the formula refers to the cumulative emission reduction, or the cumulative increase in renewable power production, relative to the Baseline conditions.

Comparison of the average cost for policy instruments, as is summarized in Table 28, indicates that the average cost for all indicators is the lowest for single policy elements aiming directly at the respective sustainability goal. The average cost per tonne of carbon emission avoided in the CO_2-cap&trade scenario is 42 \$/tC, while this cost is by 72\$ higher for the Renewable portfolio standard, which reduces carbon emissions by a significantly lower extent. Average unit costs of CO_2 reduction for the Combined-policy scenarios with carbon constraint (i.e., CO_2-cap&trade + Renewable portfolio, CO_2-cap&trade + Local externality, and CO_2-cap&trade + Local externality + Renewable portfolio) are in all cases higher than the average cost for the separate policy adoption. This cost increase is attributed to the increment in total system cost resulting from the adoption of "add-on" policy instruments, while differences in the cumulative carbon emission reduction over the Baseline are less pronounced.

SCENARIO	*Cost per unit of CO_2 reduced*	*Cost per unit of SO_2 reduced*	*Cost per unit of renewable electricity added*	*Total cost as a fraction of GDP*
	(\$/tC)	(\$/tSO_2)	(¢/kWh)	(%)
CO_2-cap&trade	42.4	4509.1	9.6	0.18
Renewable portfolio	113.9	5047.2	2.5	0.13
Local externality	85.4	2282.5	12.9	0.19
CO_2-cap&trade + Renewable portfolio	59.1	5231.0	5.1	0.25
CO_2-cap&trade + Local externality	66.8	3433.5	13.5	0.30
Local externality + Renewable portfolio	107.5	3243.7	5.8	0.28
CO_2-cap&trade + Local externality + Renewable portfolio	80.6	4100.9	7.9	0.36

Table 28. *Average undiscounted cost of policy instruments for selected group of indicators (net of taxes).*

The same observation is reported for the average cost of SO_2 emission avoided and for the average cost of renewable electricity additions. The synergetic effect of simultaneous policy adoption is, however, displayed when the average costs for the separate policy cases are summed and compared to the combined policies. Reductions in the indicator-specific average costs over the single policy cases vary between 40 to 70%, with the CO_2-cap&trade + Local externality + Renewable portfolio scenario showing the largest potential for synergies with respect to the improved sustainability indicators and the cost-efficiency.

Table 28 also indicates the magnitude of the policy-induced increases in the total undiscounted energy system cost over the Baseline scenario as a fraction of cumulative GDP projected for the computational period 2000-2050.

9.3. Robustness of scenario results

Although each of the policy instruments studied here has been tested by additional sensitivity scenarios, a more extensive parametric analysis can provide insights into the robustness of the modelling outcomes. This is particularly important for key parameters that can significantly influence the learning performance of emerging technologies, and thereby the deployment of these technologies on the energy market. Since a number of parameters used in the policy scenarios are uncertain, or are based on assumptions, a consistent sensitivity analyses can indicate, which of these parameters are the most influential, resulting in significant changes in the policy conclusions.

A full and comprehensive parametric analysis was beyond the scope of this thesis; nevertheless, a sensitivity study on the impacts of two selected parameters is carried out in this section. The first parameter is the discount rate (*dr*), and the second parameter is the learning rate (*LR*) for a group of electricity-supply technologies. Sensitivity of the GMM model to other parameters (e.g., spatial learning spillovers, annual growth rates, stochastic progress ratios, etc.) can be found in Barreto (2001).

9.3.1. Sensitivity to the choice of discount rates

The choice of discount rate implies a consideration of several aspects that are important for policy and decision making process. First, when a policy is designed that has an impact far into the future, the choice of discount rate determines the present value of policy-invoked costs (or benefits). There are two approaches to the selection of the discount rate for a long-term policy: prescriptive and descriptive approach. The former approach is based on ethical considerations that give a higher weight to the well-being of future generations, and typically results in relatively lower discount rates. The later approach proposes the use of market-based rates of discounting the future cost, while these rates are usually higher than discounting factors based on the prescriptive approach (Portney and Weyant, 1999).

Given the controversy in the proper selection of the discount rate for sustainable policies, it is advisable to evaluate the cost impacts using different *dr* values. A 5% per annum discount rate has been used in the Baseline and policy scenarios reported above. Two sensitivity cases are analysed herein for three single policy scenarios examined in this chapter, using the *dr* values of 3% and 7%. The rate of 3% is indicated by IPCC (2001a) as a rate based on "ethical" considerations. The latter value of 7% reflects more the present energy-market situation and the *dr* value is used to approximate the cost of capital invested in more risky projects (see e.g., AEN-NEA, 2005).

Figure 84 shows the change in objective function over the Baseline for the CO_2-cap&trade, Renewable portfolio and Local externality scenarios applying different discount rates of 3, 5, and 7%. For consistency, the cumulative system costs in the policy scenarios are compared to the Baseline scenarios, calculated by using the same discount rates as in the policy cases. Variations in the total cost disclose a similar trend for all policy scenarios with different *dr*. The 3%-discounting results in a total cost that is higher than in the scenarios with *dr* of 5 and 7%. The decrease in the total cost is more pronounced in the case using *dr*=7%. These changes are associated with the discounting procedure applied to the objective function in GMM, as explained in Section 3.4, Equations 5 and 6.

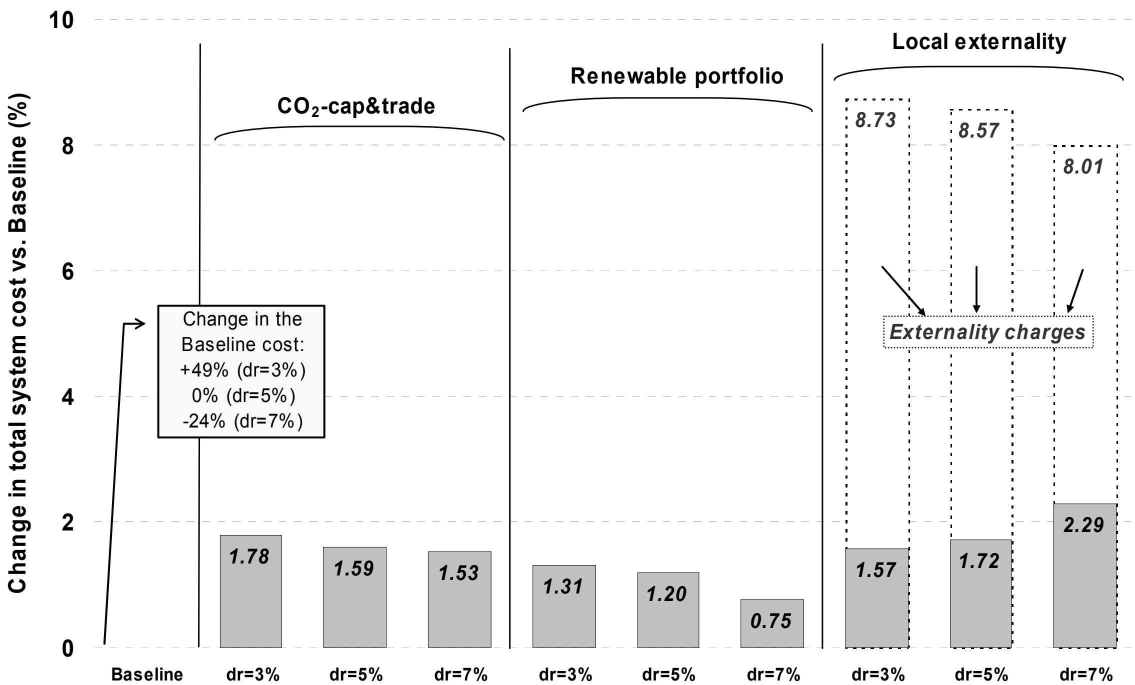

Figure 84. *Change in the cumulative discounted energy system cost relative to the Baseline scenario (excluding charges related to taxes or external cost) in relation to different discount rates. Dotted bars represent the contribution of the cumulative discounted externality charges to the relative increases in total costs for Local externality scenarios.*

An interesting observation is made for the Local externality scenario. The total discounted cost of this policy is also reduced with the higher *dr* value, but this reduction is attributed to the lesser cost of the discounted externality charges imposed on the electricity sector (being represented by dotted bars in the Figure 84). On the contrary, the technology-related discounted cost increases with the higher *dr*. This finding is explained by the fact that the stringency of the Local externality case is higher in the initial periods of the policy application (e.g., 2010-2020), as compared to the later phases. The early investments needed to adjust the energy system to the high externalities are simply more expensive if the higher *dr* is applied, and, therefore, the resulting annualised investment cost overweight the effect of the overall policy-cost discounting. This result also suggests that the policy constraints adopted in the CO_2-cap&trade and Renewable portfolio scenarios are more gradual, with the larger cost-impacts towards the end of the computational period.

The choice of the discount rate influences strongly the market penetration of electricity-supply technologies, as well as the learning performance of systems with high initial investment costs. An example of the impact of *dr* on the technology deployment under the carbon-constrained scenario CO_2-cap&trade is provided here for a group of four technologies with ETL: solar photovoltaics (SPV), gas fuel cell (GFC), natural gas combined cycle (NGCC), and the advanced coal plant with CO_2-capture.

Figure 85 illustrates the global power production from these systems under both the Baseline and CO_2-cap&trade conditions, applying different rates of discounting (i.e., 3, 5 and 7%). The largest sensitivity to the *dr* choice is reported for the SPV, which is a technology with the highest investment cost among the power supply systems represented in GMM, but also with the highest learning rate assumed. Under the carbon constraint and for the *dr* of 5 and 7%, SPV is not introduced into the model solution. Lowering *dr* to 3%, however, results in a rapid growth of SPV-installation along its maximum capacity growth rate. GFC and advanced coal with CO_2-capture play a role in the carbon-abatement process under both 3% and 5% *dr* cases. Nevertheless, an increase of *dr* to 7% prevents these technologies to gain (or increase) their market shares. Somewhat less sensitivity to *dr* shows NGCC, which is an attractive option already in the Baseline scenario. The level of penetration in 2050 is identical for the discounting by 3 and 5%, but the contribution of NGCC to the electricity mix is reduced again when *dr* of 7% applies.

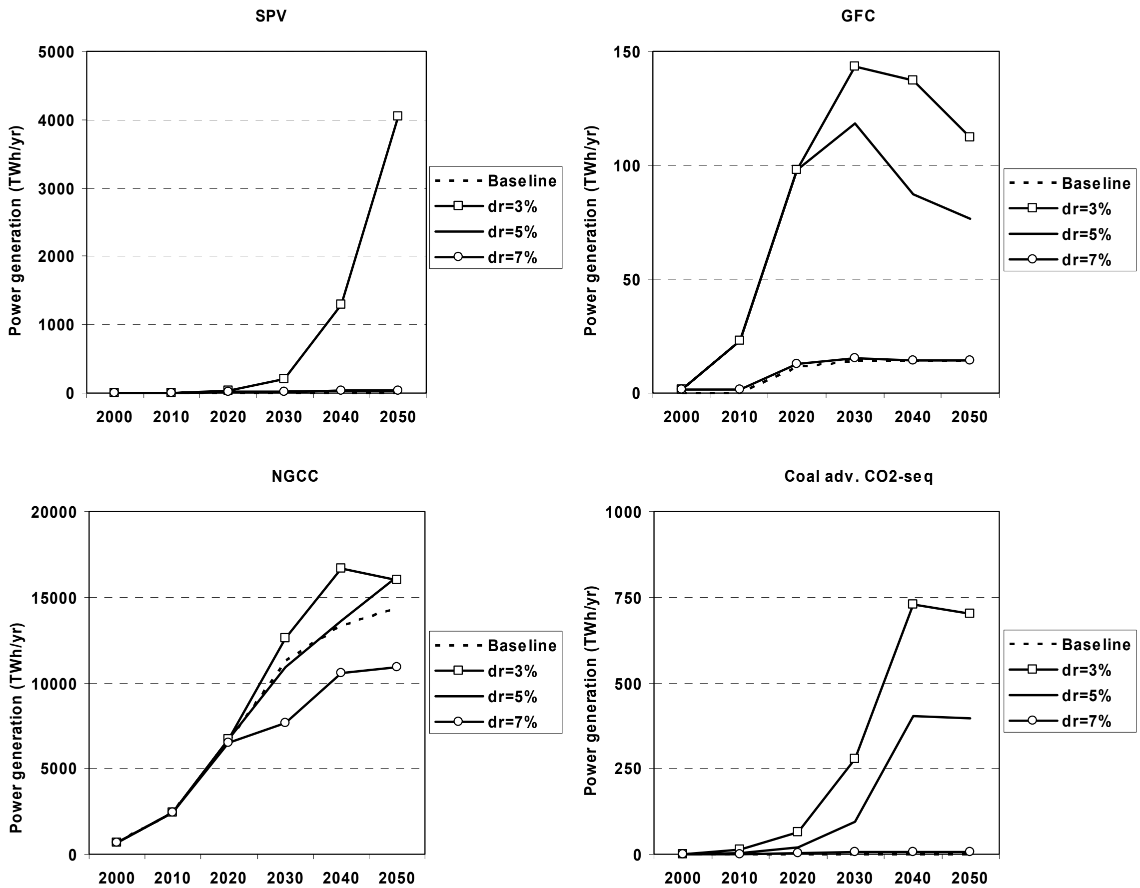

Figure 85. *Influence of the discount rate on the market penetration of selected technologies under the Baseline and CO_2-cap&trade scenario.*

Resulting changes in the market uptake of advanced fossil and renewable technologies confirm the importance of *dr* choice towards the policy adoption. A high discount rate used for investments in the electricity market may lead to "lock-outs" of emerging systems from the technology portfolio. Therefore, it is debatable whether the investments in projects leading to CO_2-abatement financed from public funds or from international banks should be discounted by using discount rates anticipated in the liberalised electricity markets rather than applying lower discount rates based on social time preference in favour of future generations.

9.3.2. Sensitivity to the learning rate

The learning rates (LR) applied to the set of power-supply systems listed in Table 10 determine the speed of investment-cost reductions, and thereby the competitiveness of a given technology under specific policy conditions, as is described in Section 3.3. Sensitivity to LR is evaluated herein for the same set of four technologies as in the antecedent sub-Section 9.3.2. Again, the CO_2-cap&trade scenario with *dr*=5% is selected for the sensitivity analysis.

The LR value in the sensitivity case is either reduced or increased by 5 percentage points as compared to the values indicated in Table 10. For the sensitivity cases, the LR value of only one technology is altered, while LRs for others remain unchanged.

Figure 86 depicts the change in the market penetration of selected technologies attendant to the LR modification. The least sensitive to LR emerges NGCC, which appears to be a robust technology option under the carbon mitigation regime. The market introduction of SPV systems is not changed when LR is increased, and this technology remains "locked-out" from the system[13]. GFC and advanced coal with CO_2-capture show more variations in the market uptake with respect to the LR value used. In the case of advanced coal with CO_2-capture, this technology is competitive already with LR=7% under the carbon constraint. Nevertheless, if the LR value is increased to 12%, the technology grows substantially following the annual (exogenously specified) market penetration limits.

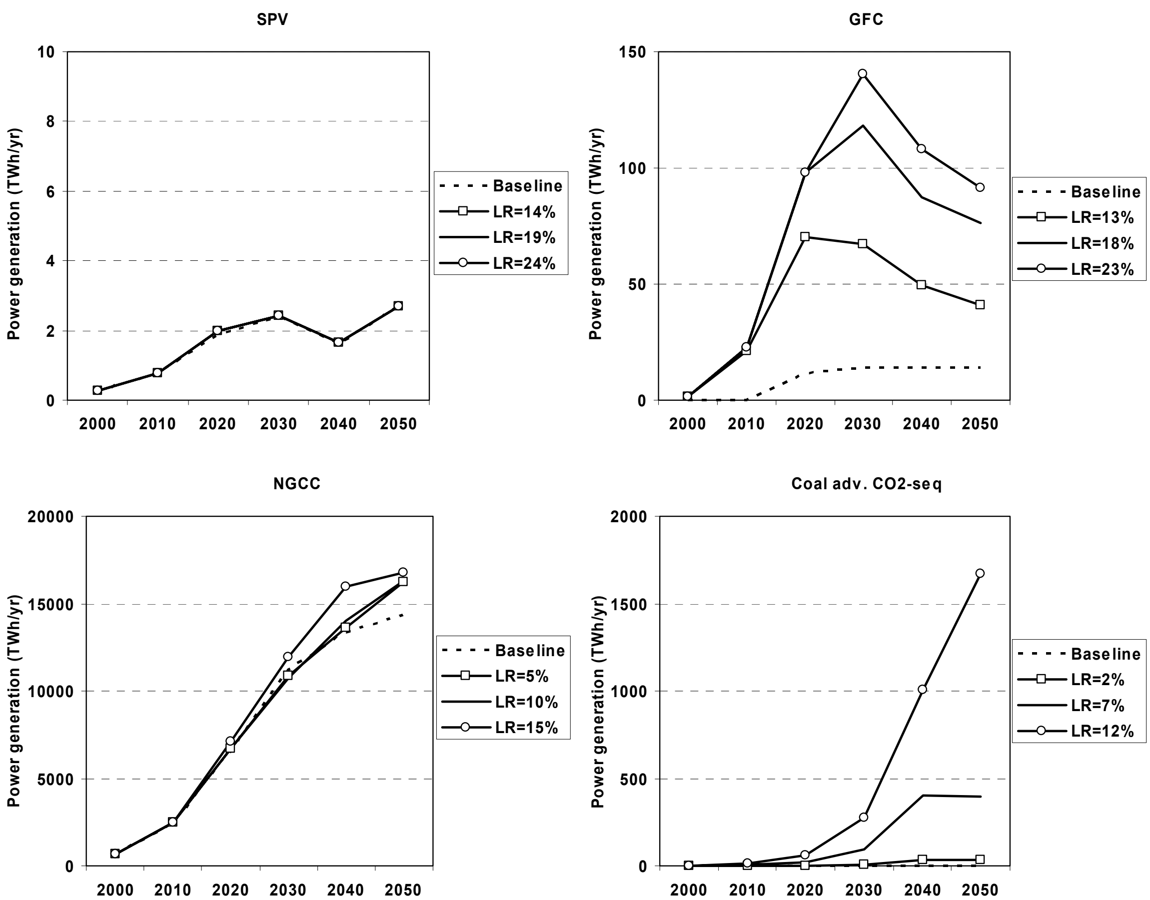

Figure 86. *Influence of the learning rate on the market penetration of selected technologies under the Baseline and CO_2-cap&trade scenario.*

[13] The marginal penetration of SPV shown in Figure 86 is forced by the lower activity bound introduced for this technology.

The sensitivity results demonstrate that for a model with the LBD capability the assumptions about the technological progress might play an influential role in the composition of the power generation mix for given policy circumstances. Especially the systems with low market shares (i.e., marginal technologies) are more sensitive to the LR assumptions.

9.4. Summary and concluding remarks

In this chapter, a synthesis of impacts invoked by three selected policy instruments addressing different aspects of sustainability in the global energy system is provided, namely the CO_2-cap&trade, Renewable portfolio standard and internalisation of Local externalities for air pollutants from electricity generation. Additionally, several combined policies where the policy elements or options are applied simultaneously are investigated (CO_2-cap&trade + Renewable portfolio; CO_2-cap&trade + Local externality; Renewable portfolio + Local externality; CO_2-cap&trade + Local externality + Renewable portfolio). Examining the effects of combining policy instruments gains important insights into potential synergies and/or trade-offs between different policy objectives, which cannot be dealt with in isolation.

Based on the synthesis of the results for single policy instruments investigated here, the following key findings are identified:

The CO_2-cap&trade scenario stabilises global CO_2 emissions to levels below 10 GtC/yr by 2050 at total system cost 1.6% higher than the Baseline scenario. Marginal abatement costs increase over the time horizon and reach a level of 145 \$/tC in 2050. A carbon-mitigation target, as defined in this study, induces important shifts in the energy system towards less carbon-intensive technologies and fuels (e.g., nuclear energy, renewables). Advanced coal-based systems equipped with CO_2-capture penetrate the electricity market and play an important role in carbon abatement.

The Renewable portfolio scheme, as modelled in this study, forces the electricity generation from renewable-energy sources to reach a global level of 35% by 2050. The associated increase in the total cost is computed to be 1.2% relative to the Baseline development. The most significant increase in generation from renewable-energy sources is reported for biomass technologies, geothermal plants, and hydroelectric power. At the end of the time horizon, SPV systems are introduced into the power generation mix at a considerable level. Growth in generation from wind turbines is significant already in the Baseline case and is approaching limits of technical potential specified for this technology. The price of green certificates resulting from the constraint applied varies between 2.6 ¢/kWh to 5.2 ¢/kWh.

Internalisation of external costs associated with air pollution emerges as the most expensive policy among the single-policy elements analysed because of substantial changes in the electricity-production system and rapid fuel switching that takes place especially during the period 2010-2020. Conventional coal-fired power plants are eliminated and replaced by advanced plants with emission control. Natural gas combined cycles, nuclear power, and renewables increase their share in the power generation mix. The inclusion of external costs in the price of electricity has positive global and local environmental impacts related to reductions in air pollution and a significant decarbonisation effect.

On the supply side of the energy system, the fossil-fuel-based systems are affected the most across all policy scenarios under investigation. The technology portfolio that emerges from the imposition of respective policy targets is comprised of natural gas combined cycle units, nuclear power plants, advanced coal power plants equipped with SO_2/NO_x scrubbers and CO_2-capture systems. Among the renewable-energy systems represented in GMM, wind, hydropower and biomass plants can play an important role in meeting specific sustainability goals.

The analysis of the role of nuclear energy performed in this chapter indicates that the rate at which nuclear power can increase its market penetration has to be assessed carefully in order to avoid unrealistic projections of the rate of nuclear-capacity additions. A substantial increase in nuclear energy use under a stringent carbon mitigation regime does not represent an acute threat from the uranium resources scarcity point of view for the time horizon of analyses, however, the cost of nuclear fuel cycle might increase without improvements in technology used.

The modelling results indicate that a range of potential synergies and ancillary benefits might result from the joint application of the different policy elements considered separately in this study. For example, internalisation of external costs from air pollution can contribute to the achievement of more ambitious carbon-emission reduction targets, as defined by the CO_2-cap&trade scenario, at a cost level that is lower than the separate adoption of both policies. According to Hourcade et al. (2001), occurrence of this environmental double dividend requires interregional transfer of financial resources for investments in advanced energy technologies and may indirectly help preventing the developing countries of Asia to remain "locked-in" coal-based energy systems.

The significant reductions in the marginal cost of green electricity and carbon permits reported for combined policy scenarios during the period 2040-2050 are attributed to the cost-reducing effect of LBD, since the combination of policy elements accelerates the learning performance of renewable and low-carbon electricity generation technologies. In the case of combining the Renewable portfolio scenario with other instruments, the policy-invoked demand reductions for electricity, too, contribute to the reduction of marginal cost of green certificates.

Finally, the secondary benefits estimated for the set of single and combined policy instruments on the basis of cumulative avoided damages due to air pollution widely exceed the increases in the total system costs. The comparison of costs and benefits associated with the portfolio of policy instruments, however, encounters uncertainties, as demonstrated here by using different methods for the valuation of external damages resulting from air pollution. Furthermore, the range of uncertainties is widened if modifications of other parameters are considered, as is exemplified in the parametric analysis of impacts of the discount rate and the learning rate on the modelling results.

A conclusion from the sensitivity model runs can be drawn that a lower discount rate favours the market uptake of emerging systems with the high initial investment cost, whereas these technologies might be "locked out" from the power generation mix in the case of a higher discounting of the future investments. The market penetration of advanced fossil and renewable energy-supply systems is also sensitive to the choice of technology-specific learning rates. Nevertheless, variations in market share reported for robust technologies (e.g., NGCC) are less sensitive to the modification of LR as compared to marginally used technologies.

10. Conclusions and policy recommendations

Current development of the global energy system constitutes a potential threat for the well being of future generations. Among the threats invoked by present patterns of energy supply and use, the most important are the human-induced global change, energy resource scarcity, insufficient access to reliable energy supplies, and, finally, the local and transboundary air pollution related to fossil-fuel combustion. Introduction of policies enabling to change the course to a desired direction of sustainability is inevitable and must be regarded within policy agendas of both industrialised as well as developing countries.

Addressing issues linked to sustainable development of the global energy system requires appropriate policy actions while taking into considerations economic, environmental and social circumstances in different world regions. Formulation and evaluation of policy measures has been a substantial research effort over the past decades. Most of the analyses, however, assess the policy impacts of single policy elements, which are often driven by the differences in preferences and priorities of the market players. Nevertheless, the complexities of crosscutting issues inherent to the sustainable energy supply and use call for exploration of a broader interconnected policy framework.

Improvement of the sustainability-performance of today's energy system can be achieved by different policy strategies. These strategies comprise regulatory measures, monetary incentives and taxes that moderate market distortions, international cooperation, and support of technological progress. Actual adoption of policy-strategies can only be successful in the long term if they are technology- and location-specific, properly timed, providing measurable impacts, but at the same time they should facilitate a certain level of flexibility allowing to moderate the policy-invoked economic burden.

Sustainable policies under investigation in this work has been implemented across five world regions following the assumption that the world-wide effort to cope with E^3 (energy-environment-economy) challenges is the only plausible way bringing tangible impacts. These impacts are explored over a time framework of 50 years, with emphasis placed on the global electricity sector, given that, among others, the reduced number of actors and the relatively wide range of technology options as compared to other sectors make it likely to be one the main targets of sustainable-energy policies.

The policy portfolio analyzed in this thesis comprises policy instruments in the areas of climate-change mitigation, promotion of renewable-electricity supply and abatement of air pollution, namely a) GHG-emissions reduction caps coupled with international emissions trading; b) Renewable portfolio and subsidy scheme complemented with international trade of green certificates; c) Internalization of externalities due to air pollutants and GHGs created by the electricity sector. Implicit to the implementation of these instruments are policy actions in favour of technological learning and knowledge spillovers for accelerated deployment of new/advanced power-supply technologies.

Furthermore, selected combinations of the policy instruments listed above have been examined in order to ascertain whether synergies, trade-offs and co-benefits can occur from their simultaneous adoption.

10.1. Implications of policy instruments for a sustainable energy system

Implications of sustainable policy instruments imposed on the reference energy system (RES) have been evaluated through energy-policy scenarios using the Global Multi-regional Markal (GMM) model. Scenario-modelling results provide a quantitative basis for comparative impact assessment of policies, their modalities and combinations. Scenarios, therefore, are used as a tool to acquire insights of how the policy-invoked energy futures are compatible with specific sustainability goals.

Based on the modelling outcomes for the policy instruments investigated, the following specific conclusions and recommendations are identified:

<u>Market-oriented flexibility mechanisms</u> help to reduce the overall cost of policy. International trading of CO_2 emissions permits, referred to as the “where” flexibility, identifies cost-efficient locations for CO_2-abatement across the world. Carbon control costs are reduced by around one third when compared to policies not allowing for carbon-permit trade. Similar results are reported for the renewable portfolio policy, where the world-wide trading with green certificates lowers the total energy system cost by 40%. This reduction is associated with allocation of the cost-efficient investment possibilities in regions with large renewable-energy potentials.

<u>Optimal timing in policy implementation</u>, i.e., the “when” flexibility, could be crucial for policy acceptability. Under the carbon cap-and-trade regime as defined in this work, the cost-optimal allocation of the global carbon budget over time produces additional reductions of 15% in the total system cost relative to the “where” flexibility option. This gain might be even

larger if the time horizon of analyses were to be extended to the second half of century. Proper timing has been found equally important for the imposition of externality charges in the electricity sector for regions relying on coal-fired power plants, where rapid structural shifts as well as significant demand cuts emerge as a consequence of the increased electricity prices.

Optimal mix of technology options, which is implicit to the MARKAL-type of policy modelling, can be extended in the case of climate-response policies by considering abatement options for non-CO_2 greenhouse gases. By inclusion of GHGs other than CO_2, the "what" flexibility is introduced that helps to identify the cost efficient mix of GHGs to be abated. Gains in total system cost from Multi-gas type of climate policies have been quantified to be of the order of 10% over the CO_2-only mitigation efforts. In other words, the total cost of climate policies is overestimated if multi-gas strategies are disregarded. Abatement of non-CO_2 'Kyoto'-gases, e.g., CH_4 and N_2O, which is indeed in many instances cheaper than curbing CO_2 emissions, might play an important role especially in the early years of policy implementation.

A single conclusion evolves as common to any kind of flexibility mechanisms considered in this study: these policy tools represent approaches to buy time. This denotes, a) policy-flexibility postpones the immediate need for investments in capital-intensive advanced technologies to later decades, and/or b) domestic efforts are bypassed with a migration of policy-actions to developing countries, where the policies are temporarily less costly. Flexibility tools have a direct link to the technological progress of advanced systems as they are based on the assumption that the new technologies will become mature in the future, thus more affordable for a large-scale application.

Nevertheless, the technological progress and transition to sustainable energy-supply patterns is not autonomous. Emerging low-emission technologies, e.g., SPV and H_2FC at the present stage of development are expensive when compared to conventional fossil-based systems; short-term-oriented markets, therefore, are likely to under-invest in those technologies. The introduction of policies to support the demonstration and deployment of low-carbon technologies, e.g., learning investments and niche markets, is a prerequisite to stimulate the respective learning processes and lead to a successful introduction to the marketplace. Policy instruments in favour of technological learning have been contrasted herein by two scenarios with ETL-option inactive. In both instances, i.e., the carbon cap&trade and renewable portfolio policies, the increase in total system cost is by 65-78% higher than has been observed under policy-scenarios allowing for 'learning-by-doing'.

Imposition of global sustainable-energy policies invokes a number of fundamental questions dealing with inter-regional income distribution, equity problems, as well as transfer of experience and know-how across regional/country boundaries. These issues have been addressed in a simplified way by this study. Neverthless, the modelling outcomes suggest that the allocation of policy-burdens has to take into account the large regional differences in human welfare, aspirations for economic growth, and political circumstances and priorities. Most notable are these complex aspects of policy-making documented for the local externality policies. Sensitivity scenarios reflecting income differences in the regional damage valuation showed that a significant improvement in the sustainability performance of the electricity system in developing countries can be achieved with externality-tax levels that are much lower than the ones applicable to the industrialised countries.

One of the most challenging tasks for sustainable energy futures is to intensify the utilisation of renewable energy sources. Application of renewable portfolio policies as formulated in this study showed that a policy target of 35-40% share of renewables in the global electricity mix by 2050 is feasible, provided issues related to impacts of the large-scale introduction of intermittent renewable sources on the power network stability can be resolved (Lund, 2005). Furthermore, the price of green certificates resulting from this policy-constraint could be competitive when compared to the present costs for electricity generation. On the other hand, application of a flat-rate subsidy scheme fails to assure a continuous market penetration of renewables beyond the years of a substantial financial incentive. In addition, this "stop-and-go" approach in technology support does not prevent "lock-outs" of less mature systems like SPVs. Clearly, the efficient policy framework in favour of renewables has to comprise both regulatory and monetary instruments, but the subsidy scheme needs to be technology-tailored to avoid potential over- and under-subsidizing.

Internalisation of external cost in the electricity sector, as an approximation of environmental tax imposed to compensate for damages, has proved to be a powerful instrument in elimination of air pollution and GHG emissions. The main problem remains in quantification and valuing of external damages incurred to the society. Internalisation of externalities emerges as the most expensive policy among the single-policy elements analysed. Scenario results confirm, however, that linking the external cost with the price of electricity changes the competitiveness of existing and future power-supply options considerably in favour of less-polluting technologies. Substantial changes in the electricity-production system and rapid fuel switching occur especially during the period 2010-2020. Furthermore, strong ancillary benefits and links are reported between the air-pollution policies and CO_2 mitigation.

10.2. Structural energy-system changes

Significant structural changes can occur on both the supply and demand side of the global energy system when stringent sustainability policies are implemented. On the supply side, the fossil-fuel-based systems are most affected. To avoid extreme costs resulting from the imposition of respective policy targets, the power-generation mix will have to consist of a portfolio of robust technology options. The technology portfolio that emerges from this analysis is comprised of natural gas combined cycle units, nuclear power plants, advanced coal power plants equipped with SO_2/NO_x scrubbers and CO_2-capture systems. Among the renewable-energy systems represented in GMM, wind, hydropower and biomass plants can play an important role in meeting specific sustainability goals.

Although NGCC is a dominating technology in the power generation profile in 2050 for all policy scenarios examined, coal remains the main source of electricity if the contributions from all types of coal-fired power plants are summed. In other words, the future global electricity system will plausibly rely to a given extend on the coal-based power generation, regardless of policy measures taken. Nevertheless, the composition of the electricity production mix for coal systems changes substantially over the time horizon, making the IGCC, PFBC and advanced supercritical power plants major market players. In the carbon-constrained policy regime adopted in this study, IGCC with CO_2-capture becomes competitive and penetrates the electricity market. It should be noted that total amounts of CO_2-sequestered in this case is well below 10% of the cumulative storage-potentials in depleted oil and gas fields estimated by IEA (2004b).

Non-hydro renewable electricity supply is largely dominated by wind turbines, which emerges to be a mature technology already in the Baseline development. Penetration of wind power is further enforced by the cost-reducing effect of LBD. Biomass (generic) power plant is the second most competitive system within the Renewable portfolio standard. This scenario is the only one where SPV gains a market share towards the end of the computation period. A break-even point for generation cost of SPV technology has been estimated at 5 ¢/kWh. Based on the modelling results, the global learning-investments necessary to reach this cost-level, by 2040, is around 280 billion US$$_{2000}$. Accumulating this immense amount of learning investment will remain a challenging task, since the market actors have to be convinced to invest in renewable-energy technologies for the initial period of their market penetration when the new systems are not competitive.

For the evaluation of the future role of the renewable electricity systems, the proper estimations of technical potentials, market growth- and learning-rates are particularly important, as these are key determinants of the results for the policy scenarios. This influence has been demonstrated by the analysis of the renewable-energy subsidy scheme as applied in the sensitivity scenario, which introduces the 'learning-by-doing' option for biomass and geothermal plants. In this case, a significant increase in the power production from these systems occurs and is sustained over the whole time horizon, in spite of the elimination of subsidies. But again, implicit to this development are early investments in systems based on biomass, for example, in regions with large biomass-fuel potentials. In this way it is also assured that the subsidies spent on a technology promotion are not lost.

The sensitivity analysis performed for the policies imposing a CO_2-constraint also demonstrates the effects of modified discount rates and learning rates on the modelling results. This analysis suggests that both parameters are influential for the competitiveness of emerging technologies under the selected policy setup. A high discount rate applied to the electricity sector might lead to "lock-outs" of promising technology options from the technology portfolio. Sensitivity to the choice of the discount rate and learning rate is technology dependent, producing variations in the market penetration particularly for marginal technologies.

Modelling results indicate that the utilization of nuclear energy will be an important component of the portfolio of carbon mitigation strategies, as well as may contribute to the abatement of air pollution. Development in the future nuclear-energy use might also influence the role of other low-carbon systems, e.g., renewables and CO_2-capture. The substantial increase in contribution of nuclear energy projected for the carbon mitigation regime analysed does not represent an acute threat from the uranium resources scarcity point of view for the time horizon of analyses. Nevertheless, the cost of nuclear fuel supplies might increase without adjustments in the technology used, particularly for costs related to the "back-end" of the nuclear fuel cycle. Technology improvements that can be foreseen to maintain competitiveness of nuclear power comprise: higher burn-up rates of nuclear fuel, life time extension of existing and future reactor units, construction time reduction, utilisation of unconventional fissile materials, and advanced fuel cycles that deal with the growing waste problem(s).

When discussing the future role of nuclear energy, it has to be stressed that this technology is associated with a number of obstacles that can not be omitted by the policy- and decision-making process. For example, the projected large growth in the nuclear capacity additions has to be realised carefully while taking into consideration additional aspects such as the political and social acceptance, spent-fuel and radioactive waste disposal, training of operators, proliferation, and risks of severe accidents. These concerns cannot be addressed by bottom-up energy models; however, they belong to factors that will determine the future position of nuclear technology in the global energy supplies.

On the end-users side of the energy market, it has been found that policies imposed might increase the price of electricity and fossil fuels; therefore, a reduction in final energy demand together with fuel substitution takes place. At the end of time horizon examined, the largest reduction in total final-energy use as compared to the Baseline is reported for the carbon policies, because they are imposed on the entire reference energy system. On the other hand, the demand for electricity is reduced the most under the renewable portfolio policy. Under the policy-scenarios presented here, the consumption of electricity is lowered in both industrial and residential&commercial sectors, while the transport sector is not affected. The largest demand-cuts are observed in the industrial sector, since this sector shows the greatest ability to switch from electricity to other fuels. The policy-invoked end-use demand reductions also contribute to the fulfilment of the carbon-abatement targets and the decreasing dependency on fossil fuels, although this contribution is not substantial in comparison with other mitigation components.

10.3. Environmental and cost impacts

The policy options under examination here suggest varying potentials to reduce energy-related GHG emissions and air pollution at different cost levels. The extent and cost of the policy-induced emissions mitigation is determined by a) the severity of the policy constraint relative to the Baseline; b) the timing and effectiveness of the respective policy implementation in different world regions; c) the emission-permits trade specification; d) the dynamics of technology change (ETL); and, finally, e) the deployment of the emission-control technologies. Furthermore, various cross-policy interactions contribute to the emission-abatement effects of policies when adopted concurrently.

The marginal CO_2-abatement cost, which corresponds to the price of carbon-permits traded globally, have been analysed for policies where explicit CO_2- or C-eq- reduction targets apply. Under the CO_2 cap-and-trade policy, the regional CO_2 allowances are specified such that global CO_2-emissions are constrained to levels below 10 GtC/yr by 2050. The selected emission trajectory enables achieving a 550-ppmv stabilisation goal of the atmospheric CO_2 concentration in the long run. The resulting <u>marginal costs of carbon abatement vary across scenarios and increase over time</u>, reaching a level of 145 $/tC in 2050. Allowing for "when" and "what" flexibility reduces the price of carbon equivalents by 20% and 28%, respectively. The cost reduction in the multi-gas abatement strategy is remarkable since this scenario forces a larger cumulative emission reduction relative to the "where" and "when" flexibility cases.

<u>Internalisation of externalities invokes a strong decarbonisation effect</u>. The most significant reduction in CO_2 emissions with respect to the Baseline scenario are achieved between 2010 and 2020, and the reduction exceed the targets of the climate policies. These early emission-cuts result from a substantial fallback of the coal-based power generation implicit to the premature retirement of existing coal-fired plants without SO_2/NO_x control. The Renewable portfolio policy reduces the global carbon-emission rates by around 10% in 2050. This reduction is linked directly to the 35%-share of renewable technologies in the power generation mix, as well as to the invoked reductions in coal and natural gas use for electricity production.

Among the policy instruments studied, the largest <u>reductions in SO_2 and NO_x emissions</u> from the electricity sector over the reference (no-sulphur/NO_x-policy) development of up to 85% and 65% are reported for the externality scenarios, which explicitly account for damages related to air pollution. The substantial decrease in both emittants is attenuated towards the end of the time horizon, wherein the advanced fossil-fuelled systems regain market share. The modelling results further indicate a significant reduction in SO_2 and NO_x emissions in 2050 as of 52% and 47%, respectively, invoked indirectly by the long-term carbon-mitigation policies. A similar effect has been found for CH_4 emissions under CO_2-only abatement policies. In this case, the reduction of methane emissions up to 20% in 2050 over the Baseline scenario occurs because of a strong decrease in the production and use of fossil fuels.

The presented analysis suggests that the non-internalised externalities from the electricity sector due to air pollution and global warming might add nearly 24% to total cumulative costs of the reference energy system within the next 50 years. This external cost is not taken into account in the price of electricity, but is imposed on the society in a form of environmental and health damages. The cumulative undiscounted damages produced by the power generation sector in the non-SO_2/NO_x-policy Baseline scenario, as estimated herein, totals up to 113 trillion $ for the years 2010-2050, which corresponds to about 3% of the cumulative global GDP_{mex} projected for this period. Although the quantification of future damages is surrounded by a number of uncertainties, an important conclusion is that the overall damages in the Baseline are largely dominated by those from air pollution alone, which creates a considerable potential for secondary benefits from policies aimed at CO_2 mitigation.

Sustainability performance of the global energy system can be also measured by the projected reliance on, and depletion of, carbon-intensive or scarce fossil fuel supplies. An assessment of this indicator provided only limited insights because the policy tools analysed in this study are targeted primarily at the electricity sector, with the exception of climate-response policies. Nevertheless, some trends can be summarised as follows: within the sustainable policy set investigated here, by far the most affected primary-energy carrier is coal, but considering the abundant hard coal reserves, this finding is less relevant for sustainable futures. Reduction in the use of natural gas in comparison to the reference development in 2050 is most pronounced under the renewable portfolio policies, where the higher share of renewables forces the NGCC plants out from the generation mix.

Dependency on oil consumption fluctuates heavily over the time horizon, because oil substitutes for the electricity demand-cuts in the industrial sector between 2020-2040. As expected, the largest reduction in oil use over the Baseline is observed under the carbon policy-constraint, and totals to -6% in 2050. To conclude, an alternative policy setup that would extend the scope of renewable and externality policy instruments to other sectors, namely the heating and transportation sectors, might lead to a much stronger switching from conventional (fossil) energy carriers towards alternative fuels like biomass, alcohols, hydrogen, etc., on the demand side of the global energy system.

10.4. Secondary benefits versus trade-offs and synergies

The last part of the conclusions is dedicated to a group of adjacent phenomena attendant to the adoption of sustainable energy policies. Secondary or ancillary benefits for emission reductions have already been outlined in the previous section. These benefits can be quantified in terms of the avoided damages related to local and transboundary air pollution or from climate change, depending on the policy goal. Recognising the difficulties of reaching international agreements on climate-response strategies, secondary benefits of GHG-abatement should be considered up-front by policymakers. The results of this study suggest that the ancillary benefits can be large, in particular for the developing regions, and in fact may exceed the direct costs of CO_2 mitigation.

Strong indications are evident that a range of potential synergies might result from the joint application of the different policy elements considered separately in this study. For instance, internalisation of externalities from air pollution in combination with a CO_2-cap can achieve a more ambitious carbon-emission reduction at a cost level that is lower than the sum of costs for separate adoption of both policies. Moreover, an analysis of the time evolution of the marginal cost of green certificates and carbon permits in the combined policy scenarios indicates that the simultaneous adoption of policy instruments accelerates the learning performance of renewable and other low-carbon electricity generation technologies. Nevertheless, trade-offs associated with pursuing different sustainability goals concurrently have to be identified and addressed when designing a combined policy framework to assure its feasibility and acceptability.

Synergetic effects and secondary benefits of policy instruments adopted simultaneously might together provide a sustainability double dividend, which may be especially large in regions relaying on coal. Referring to Hourcade et al. (2001), occurrence of this double dividend is conditional on the achievement of environmental improvements in the same region, which requires interregional transfer of financial resources for investments in advanced energy technologies through flexibility mechanisms. In addition, combined policies may indirectly prevent developing regions of, e.g., Asia, from staying locked into a coal-based energy system.

10.5. Final message

Impact assessment of policy instruments for sustainable energy systems requires a linkage between varieties of sustainability strategies and must involve a consideration of the needs of both developing and industrialised countries. Investigation and quantification of the effects of separate and combined policy instruments has to take into account the inertia in the utilisation of existing supply options, related infrastructures and the production↔consumption patterns, among others.

The results presented in this study depend on the particular baseline scenario adopted as a reference point of departure, as well as are depending on specific assumptions made about energy-technology dynamics, future availability of energy carriers and development of energy demands of the next generations. The insights derived from this extensive modelling exercise, however, illustrate the benefits that the set of single and combined sustainability strategies might offer.

A portfolio of "win-win" policies based on support of new technologies, cap-and-trade actions for GHG-mitigation in combination with a realistic renewable portfolio scheme and coupled with policies that gradually internalise external costs incurred from energy production, might together form key constituents of a roadmap leading towards a sustainable global energy system. These combined policies also result in reduced dependency on fossil-fuel supplies, and in a more resilient energy and social systems with improved local and global environments.

10.6. Outlook for further research

Two groups of further research areas emerge from the results of this study. The first proposes directions for enhancement of the modelling framework. The second group addresses issues that could extend the scope and profoundness of impact assessment of the selected policy-portfolio.

The GMM model could be extended to define the emission trajectories for climate models in order to study changes in CO_2 concentrations, temperature change and sea-level rise induced by different policy instruments. For such a purpose, future work could be oriented towards linking GMM with a climate model, e.g., C-Goldstein (Marsh et al., 2002) via the analytical cutting plane algorithm (Drouet et al., 2005) and to coupling GMM with a simplified macro-economic model (Kypreos, 1996). By following this path, an Integrated Assessment Model (IAM) could result that couples a bottom-up representation of the energy-system linked with a general circulation model in a way that takes into account macro-economic feedbacks. Such an IAM would enable studying the effects of policy actions related to energy and the environment on climate change and the corresponding economic impacts in the context of sustainability.

To make GMM suitable for linkage to a climate model, several enhancements are required, such as the extension of the time horizon to 2100 or beyond, and to complete the representation of CO_2 and non-CO_2 GHGs accounting for emission sources from, e.g., cement production, iron working and agriculture using, for instance, the updated data sets from EMF21 (2005). To increase the regional resolution allowing for more region-specific policy conclusions, some regions could be modelled separately, namely Western Europe, Japan, the Russian Federation, China and India.

Extension of the LBD modelling capability of GMM could comprise incorporation of algorithm that allows for learning spillovers of “key” learning-components across technology clusters (Seebregts, 2000). In addition, simulation of the impacts of RD&D expenditures on technological learning might be addressed in the model development. Also, to avoid possible underestimation of ETL effects in non-electric sectors, future work should focus on extending endogenized technology learning to other non-electric sectors, e.g., transportation and fuel production. This extension is related closely to another possible model-enhancement task, which refers to a dissagregation of end-use demand sectors, in particular the transport sector, which ought to be differentiated into passenger and freight modes.

Impact assessment of policies using energy-scenarios offers numerous possibilities for further analyses. Despite a number of sensitivity scenarios have tested the set of policy instruments under survey here, an extended systematic sensitivity analysis might provide additional insights into the robustness and implications of the policy assessment. The sensitivity parameters that could be studied comprise technology-specific discount rates of future investments and potential damages, learning rates for electricity supply and demand technologies, as well as price elasticities of demand sectors. The MARKAL model allows also for conducting stochastic analyses of the aforementioned parameters to assess the impacts of uncertainties on the policy conclusions.

Analysis of impacts of international trading of CO_2-permits and green certificates can be enhanced by studying the role of transaction costs in the policy implementation. Combining policies that address transboundary air pollution and climate change could include the consideration of the international trading schemes for SO_2/NO_x allowances. Furthermore, impacts of present domestic and international policies on the long-term time evolution of SO_2/NO_x emission pathways might be a focus of interest, since these emittants, too, influence the climate response of the atmosphere.

The valuation of external damages incurred in different regions should be based on detailed "bottom-up" analyses using the region-specific impact pathways and dose-response functions (EC, 1999b). Implementation of externality taxes in energy scenarios could be also extended beyond power generation to other sectors of the energy system, i.e., transport, industry and heating sectors. Finally, a multi-criteria analysis (e.g., Haldi and Pictet, 2003) could eventually be performed for the portfolio of selected policies and their combinations, considering multiple social, economic, as well as environmental and health aspects of sustainable development.

Nomenclature/abbreviations

Calculation of multiples of the units		
Acronym	***Name***	***Multiple***
k	Kilo	10^3
M	Mega	10^6
G	Giga	10^9
T	Tera	10^{12}
P	Peta	10^{15}
E	Exa	10^{18}

¢	Cent (10^{-2}\$)
$	USA Dollars
€	Euro
η	Conversion efficiency,”eta”
ACROPOLIS	Assessing Climate Response Options: Policy Simulation project
ACT	Activity
AF	Adjustment factor
ANNEX B	List of countries with reduction targets included in the Kyoto Protocol
ASIA	Centrally Planned Asia, India, South-East and Pacific Asia
B2	“Dynamics-as-usual” family of scenarios defined by SRES
C	Carbon
C-eq	Carbon equivalent
cap	Capita
CAP	Capacity
CDM	Clean development mechanism
CGE	Computable general equilibrium model
CH_4	Methane
CHP	Combined heat and power (cogeneration)
CI	Carbon intensity
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon Dioxide
DEDUST	Dust removal

$DeNO_x$	Nitrogen oxides abatement, denitrification
$DeSO_x$	Sulphur oxides abatement, desulphurisation
dr	Discount rate
EC	European Commission
ED	Elastic Demand (MARKAL)
EEFSU	Eastern Europe and Former Soviet Union
ERIS	Energy Research and Investment Strategy model
ETHZ	Swiss Federal Institute of Technology Zürich
ETL	Endogenous technological learning
EU	European Union
ExternE	Externalities of Energy
FC	Fuel Cell
F-gas	Fluorinated gases
FGD	Flue gas desulphurisation
GDP	Gross domestic product (T$/yr)
GFC	Gas fuel cell (based on natural gas)
GHG	Greenhouse gas
GMM	Global Multi-regional Markal model
GWP	Global warming potential
HFCs	Hydrofluorocarbons
H_2FC	Hydrogen fuel cell
IAM	Integrated assessment model
IEA	International Energy Agency
IET	International Emissions Trading
IGCC	Integrated coal gasification combined cycle
IIASA	International Institut for Applied Systems Analysis
IPCC	Intergovernmental panel on climate change
J	Joule
JI	Joint Implementation
LAFM	Latin America, Africa, and Middle East region
LBD	Learning-by-doing
LR	Learning rate

LWR	Light water reactor
MAC	Marginal Abatement Cost
MACRO	Macro-economic (sub)module
MARKAL	Market allocation model
MERGE	Model for Evaluating Regional and Global Effects of GHG Reduction Policies
MESSAGE	Model for Energy Supply Strategy Alternatives& their General Environmental Impact
mex	Market exchange rate
mill	Mills (10^{-3}\$)
MOX	Mixed oxide fuel (UO_2+PuO_2).
n.a.	'Not applicable'
NAME	North American region
NCCR	National Centre of Competence in Research
NGCC	Natural gas combined cycle
NNU	New (design of) nuclear power plant
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
O_3	Ozone
O&M	Operation and maintenance
OECD	Organization for Economic Cooperation and Development
OOECD	Other OECD region: Western Europe, Japan, Australia, and New Zealand
PE	Primary energy
PFBC	Pressurised fluidised bed combustion
PFCs	Perfluorocarbons
PM	Particulate matter
Pop	Population
POPs	Persistent Organic Pollutants
ppmv	Parts per million by volume
ppp	Purchasing power parity
pr	Progress Ratio
PSI	Paul Scherrer Institut
Pu-239	Isotope of plutonium
RD&D	Research, development and demonstration

RES	Reference Energy System
seq	Sequestration
SF_6	Sulphur hexafluoride
SO_2	Sulphur dioxide
SPV	Solar photovoltaic system
SRES	Special report on emission scenarios
T&D	Transport and distribution
t	Tons, metric tonnes (10^3 kg)
tC	Tonnes Carbon
tCO_2	Tonnes Carbon Dioxide[14]
tm	technical-progress multiplier
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
VLYL	Value of a Life Year Lost
VOC	Volatile organic compound
W	Watt
Wh	Watt-hour
WTP	Willingness to pay

[14] The conversion of tonnes of carbon to tonnes of carbon dioxide is 1tC = 44/12 tCO_2

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Curriculum vitae

Personal Data

Name: Peter Rafaj

Date of birth: September 25th, 1972

Place of birth: Piešťany, Czechoslovakia

Nationality: Slovak

Education

2001 – 2005	Swiss Federal Institute of Technology Zürich (ETHZ), Switzerland; Doctoral student at the Department of Chemistry and Applied Biosciences (D-CHAB).
1998 – 1999	University of Amsterdam, The Netherlands; European postgraduate course in environmental management, Interfaculty of Environmental Sciences.
1995	Danish Technical University, Lyngby, Denmark; Department of Electrophysics and Department of Geotechnics, programme TEMPUS.
1990 – 1995	Comenius University Bratislava, Slovakia; Faculty of Natural Sciences, Department of Applied and Environmental Geophysics.
1986 – 1990	Gymnasium Piešťany, Slovakia.

Working Experience

2001 – 2005	Paul Scherrer Institute (PSI), Switzerland; Energy Economics Group - research assistant.
2000 – 2001	Energy Centre Bratislava (ECB), Slovakia; Technical and Project Department - project management and development.
1997 – 1999	Nuclear Power Plants Research Institute Inc. (VUJE), Slovakia; Division of Information Technologies - research assistant.
1997	Nuclear Regulatory Authority of the Slovak Rep. (UJD); Technical Support Department - project assistant.
1995 – 1997	Institute of Preventive and Clinical Medicine (UPKM), Slovakia; Department of Radiation Protection - civil service.