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PLANETS

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Scientific Publications

Energy Research Centre of the Netherlands

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1. Introduction

To ensure the maximum visibility and trustworthiness of the research work in PLANETS, the methodology used in the various phases of the project as well as the final results have been organized in scientifically edited publications, submitted to international journals.
A special issue, dealing with the construction of stochastic scenarios using the different approaches to handle uncertainty in the different classes of Energy/Economy/Envronment (E3) integrated assessment models that appear in PLANETS, will be published in the peer reviewed journal "Environmental Modelling and Assessment".
Moreover several other publications have been produced, including: working papers, publications in scientific journals and a policy brief.

2. Special Issue

A special issue, dealing with the construction of stochastic scenarios using the different approaches to handle uncertainty in the different classes of Energy/Economy/Envronment (E3) integrated assessment models that appear in PLANETS, will be published in the peer reviewed journal "Environmental Modelling and Assessment".
The abstracts of the papers submitted to the "Environmental Modelling and Assessment Journal" are reported here below.

2.1 A Stochastic Control Model for Optimal Timing of Climate Policies

Authors: O. Bahn , A. Haurie and R. Malhamé

Foreword. This paper is based on the following publication: O. Bahn, A. Haurie and R. Malhamé, A stochastic control model for optimal timing of climate policies, automatica, 44:1545-1558, 2008.

Abstract. A stochastic control model is proposed as a paradigm for the design of optimal timing of greenhouse gas (GHG) emission abatement. The resolution of uncertainty concerning climate sensitivity and the technological breakthrough providing access to a carbon-free production economy are modeled as controlled stochastic jump processes. The optimal policy is characterized using the dynamic programming solution to a piecewise deterministic optimal control problem. A numerical illustration is developed with a set of parameters calibrated on re cently proposed models for

integrated assessment of climate policies. The results are interpreted and the insights they provide on the timing issue of climate policy are discussed.

Keywords. Climate policies, environmental hedging strategies, piecewise deterministic markov process, stochastic control

2.2 Hedging against climate policy and technology uncertainty: implications for technology mix and policy instrument choice

Authors: E. De Cian and M. Tavoni

Abstract. There is considerable uncertainty over future climate policies and abatement costs of low carbon technologies, with important implications for the optimal investment portfolio and the costs of meeting climate stabilization objectives. Such sources of uncertainty are also motivating the discussion about policy instruments choice, and the role of regulation as a complement to market based approaches in order to diversify away both risks. In this chapter we analyze this issue by using a stochastic programming version of an integrated assessment model to evaluate the effect of uncertainty in future carbon prices and technology costs of three main low carbon power generation technologies. We assess the implications of either and both risks on the optimal technology mix under a variety of assumptions and evaluate the potential for regulation on emissions performance and renewable portfolio in accompanying a market based climate policy.

Keywords. Climate change, Information and uncertainty, Environmental policy

2.3 Evaluating Carbon Capture and Sequestration in Perspective of the Very Long Term

Authors: R. Gerlagh and B.C.C. van der Zwaan

Abstract. Climate change research with the economic methodology of cost-benefit analysis is challenging because of valuation and ethical issues associated with the long delays between emissions and potential damages, typically over 100 years and more. The large uncertainties by which climate change impacts are characterised and the possibly temporary nature of some CO2 abatement options exacerbate this challenge. For example, potential leakage of CO2 from geological reservoirs once this greenhouse gas has been stored artificially underground for climate control reasons requires an analysis in which the uncertain climatic consequences of leakage are valued over many centuries. We present a stylized discussion of some of the relevant questions in this context and provide preliminary calculations with the top-down integrated assessment model DEMETER, which we extended for this purpose to cover a time span until the year 3000.

Keywords. Climate change, carbon dioxide emissions, climate control, CO2 capture and storage (CCS), geological leakage

2.4 Modeling Uncertainty in a Large scale integrated Energy-Climate Model

Authors: M. Labriet , R. Loulou and A. Kanudia

Foreword. This paper is based on the following publication: M. Labriet, R. Loulou and A. Kanudia. Modeling Uncertainty in a Large scale integrated Energy-Climate Model. In J.A. Filar and A. Haurie, editors, Uncertainty and Environmental Decision Making: A Handbook of Research and Best Practice. Springers International Series in Operations Research and Management Science, p51-77, 2009.

Abstract. The well-known method of stochastic programming in extensive form is used on the large scale, partial equilibrium, technology rich global 15-region TIMES Integrated Assessment Model (ETSAP-TIAM), to assess climate policies in a very uncertain world. The main uncertainties considered are those of the Climate Sensitivity parameter, and of the rate of economic development. In this research, we argue that the stochastic programming approach is well adapted to the treatment of major uncertainties, in spite of the limitation inherent to this technique due to increased model size when many outcomes are modeled. The main advantage of the approach is to obtain a single hedging strategy while uncertainty prevails, contrary to classical scenario analysis. Furthermore, the hedging strategy has the very desirable property of attenuating the (in)famous 'razor edge' effect of Linear Programming, and thus to propose a more robust mix of technologies to attain the desired climate target. Although the examples treated use the classical expected cost criterion, the chapter also presents, and argues in favor of, altering this criterion to introduce risk considerations, by means of a linearized semi-variance term, or by using the Savage criterion. Risk considerations are arguably even more important in situations where the random events are of a 'one-shot' nature and involve large costs or payoffs, as is the case in the modeling of global climate strategies. The chapter presents methodological details of the modeling approach, and uses realistic instances of the ETSAP-TIAM model to illustrate the technique and to analyze the resulting hedging strategies. The instances modeled and analyzed assume several alternative global temperature targets ranging from less than 2◦ C to 3◦ C. The 2.5◦ C target is analyzed in some more details. The study makes a distinction between random events that induce anticipatory actions, and those that do not. The first type of event deserves full treatment via stochastic programming, while the second may be treated via ordinary sensitivity analysis. The distinction between the two types of event is not always straightforward, and often requires experimentation via trial-and-error. Some examples of such sensitivity analyses are provided as part of the TIAM application.

Keywords. Energy modeling, Uncertainty, Stochastic programming, Hedging strategies, Climate policies, Technology.

2.5 The role of CCS in long-term climate mitigation: the impact of uncertain CO2 storage availability

Authors: I.J. Keppo and B.C.C. van der Zwaan

Abstract. A major characteristic of the long term climate energy system is the large uncertainty concerning both, the future environmental requirements as well as the tools available for fulfilling these. One potential key technology for bridging the transition from the current fossil dominated energy system to a more sustainable one is carbon capture and storage. However, there are large uncertainties concerning the large scale implementation of this technology, one being the regional availability of storage sites for the captured carbon. We approach the issue from an energy system perspective and use the energy system model TIAMEC to study a set of scenarios covering a range of climate targets and technology futures, from two angles; 1) a sensitivity analysis consisting of a number of scenario that assume perfect foresight for the decision making and 2) a stochastic programming set-up, which allows the model to consider all included potential future states simultaneously. We find that if a very stringent target is a possibility, it dominates the solution; if deep reductions are not started as soon as possible, the target may become unreachable. However, reaching the stringent target comes at an exceedingly high price, indicating that e.g. adaptation measures, or even climate damages, might be preferable to the very high mitigation costs this target suggests.

Keywords. Climate change, energy systems modelling, carbon capture and storage (CCS), uncertainty

2.6 Robust Optimization for Environmental and Energy Planning

Authors: F. Babonneau , J.-P. Vial , and R. Apparigliato

Foreword. This paper is based on the following publication: F. Babonneau, J.-P. Vial, and R. Apparigliato. Robust optimization for environmental and energy planning. In J.A. Filar and A. Haurie, editors, Uncertainty and Environmental Decision Making: A Handbook of Research and Best Practice. Springers International Series in Operations Research and Management Science, 2009.

Abstract. Uncertainty is often present in environmental and energy economics. Traditional approaches to optimization under uncertainty, e.g., stochastic programming, chance-constrained programming or stochastic dynamic programming, encounter the most severe numerical difficulties because models in this area are large and complex,

already in their deterministic formulation. The goal of the present chapter is to introduce a relatively new field, known as robust optimization, as an alternative to traditional methods and formulations. Through an illustrative example, we suggest ways of putting robust optimization at work in environmental and energy optimization models.

Keywords. Robust optimisation, energy planning model.

2.7 Energy Security: a Robust Programming Approach and Application to European Energy Supply via TIAM

Authors: F. Babonneau , A. Kanudia , M. Labriet , R. Loulou and J.-P. Vial

Abstract. Energy supply routes to a given TIAM region (say E.U.) are subject to randomness, resulting in partial or total closure of a route (corridor). For instance: a pipeline may be subject to technical problems that reduce its capacity. Or, oil supply by tanker may be reduced for political reasons or because of equipment mishaps at the point of origin, or again by a conscious decision by the supplier in order to obtain economic benefits. This chapter uses the approach of Robust Optimization to model uncertainty on the energy supply constraints for Europe in the economy-energy model TIAM. The resulting formulation provides several interesting features regarding the security of EU energy supply and has also the advantage, and not the least, to be numerically tractable.

Keywords. Energy supply, Robust Optimization, Ambiguous Chance Constraint Programming, TIAM.

2.8 Perspectives of CCS in Europe considering technical and economic power plant uncertainties

Authors: T. Kober and M. Blesl

Abstract. The perspectives of power plants with carbon capture and storage (CCS) in Europe are analysed with the Pan-European TIMES model (TIMES PanEU) incorporating technical and economic uncertainties of CCS technologies by the use of the Parametric Programming routine. Thereby the analysis considers two different climate policy regimes for Europe.
The market share of CCS power plants is highly influenced by the climate policy. Under an ambitious climate policy regime (greenhouse gas reduction 83% in 2050 compared to Kyoto base) the electricity demand increases up to 6500 TWh in 2050 in the EU-27 plus Norway, Switzerland and Iceland (EU-27+3), with a high contribution of CCS power plants (almost 40%). The technical and economic parameters of CCS power plants can determine the market share significantly. Especially in early periods (2020 and 2030) and less tight GHG reduction obligations in 2040 and 2050 the enhancement

of the performance of CCS technologies can cause additional electricity generation from CCS power plants up to 600 TWh for the EU27+3. Thereby improvements of capture performance can lead to additional electricity quantities to the system, satisfying the growing demand and to the substitution of alternative electricity generation technologies, e.g. natural gas combined cycle without CCS.
Regarding the influence of future CCS power plant parameters the analysis shows that in early periods (2020 and 2030) reductions of invest costs have a higher impact on the electricity generation from CCS power plants since CCS power plants are primary based on solid fossil fuels, and their economics are consequently stronger influenced by invest costs than efficiency improvements. In later periods (2040 and 2050) more natural gas fired CCS power plants operate on the market, which are more sensitive to fuel prices and thus efficiency improvements have a higher effect on these technologies.

Keywords. Carbon capture and storage, Europe, energy system, climate policy, technology adoption, parametric programming.

2.9 Uncertainty and Economic Analysis of Energy and Climate Policies using TIAM and GEMINI-E3 models

Authors: F. Babonneau , M. Vielle , A. Haurie and R. Loulou

Abstract. In this paper we use the computable general equilibrium model GEMINI-E3 with randomly generated uncertain parameter values to provide a stochastic micro- and macroeconomic analysis of a hedging emission policy identified by the Times integrated assessment model TIAM, run in a stochastic programming version.

Keywords. Stochastic programming, Monte-Carlo sampling, GEMINI-E3.

3. Other scientific publications

Several other scientific publications have been produced within the PLANETS project, including: working papers, publications in scientific journals and a policy brief.

The abstracts and/or short descriptions of these scientific (peer reviewed) publications are reported here below.

3.1 Nuclear versus Coal plus CCS: A Comparison of Two Competitive Base-load Climate Control Options (FEEM Note di Lavoro , n. 2009.1, 2009; Environmental modeling and assessment, forthcoming).

Authors: Massimo Tavoni and Bob van der Zwaan

Abstract. In this paper we analyze the relative importance and mutual behavior of two competing base-load electricity generation options that each are capable of contributing significantly to the abatement of global CO2 emissions: nuclear energy and coal-based power production complemented with CO2 capture and storage (CCS). We also investigate how, in scenarios developed with an integrated assessment model that simulates the economics of a climate-constrained world, the prospects for nuclear energy would change if exogenous limitations on the spread of nuclear technology were relaxed. Using the climate change economics model WITCH we find that until 2050 the growth rates of nuclear electricity generation capacity would become comparable to historical rates observed during the 1980s. Given that nuclear energy continues to face serious challenges and contention, we inspect how extensive the improvements of coal-based power equipped with CCS technology would need to be if our economic optimization model is to significantly scale down the construction of new nuclear power plants.

Keywords. Economic competition, electricity sector, nuclear power, coal power, CCS, renewables, climate policy.

3.2 The role of international carbon offsets in a second-best climate policy: A numerical evaluation (*FEEM Note di Lavoro* , n. 2010.33, 2010).

Authors: Enrica De Cian and Massimo Tavoni

Abstract. International carbon offsets have been promoted since the Kyoto Protocol and an increasing number of countries have implemented or proposed cap-and-trade schemes with international trading, even though with quantitative or qualitative restrictions. Those limits reflect the trade-off between economic efficiency, distributional issues, and the need for additionality of foreign mitigation measures. Ceilings are also justified on the ground that international offsets undermine the capability of climate policy to induce and diffuse technological change.
This paper addresses these issues in a second-best setting that explicitly considers the interplay between multiple externalities. We evaluate numerically how limits to the size, the timing, and the participation to an international carbon market affect the macroeconomic costs of climate policy, international financial transfers, and the incentive to carry out innovation.
Results indicate that when constraints on international offsets are moderate, such as limiting their use to at most 15% of regional abatement, efficiency losses are small because they are partly compensated by more technological change and energy market effects, although specific regional patterns are identified. Regarding financial outflows from OECD countries, already a 15% ceiling would limit financial transfers significantly. Provisions of this kind are in line with some of the most recent policy proposals in OECD countries.

3.3 Implications of different climate protection regimes on the EU-27 and its member states till 2050 (to be submitted).

Authors: M. Blesl, T. Kober, R. Kuder, D. Bruchof

Abstract. To limit the increase of global warming to an acceptable quantity, a clear reduction of global greenhouse gas emissions is necessary. But not the need for a reduction is discussed, key issue is the break down of the reduction targets between the different world regions or even countries.
Therefore, the project Planets funded by the European Commission evaluated the cost optimal global burden sharing to reach a global emission reduction target. This result of global modelling is an optimal split between the world regions and is the initial point of this study. Given different reduction pathways for Europe (depending on the global target, commitments of the world regions and trade possibilities), the optimal ways to reach these targets and the impact on the European energy system are analysed.
The study evaluates how Europe can contribute in a cost optimal way to keep global greenhouse gas emissions below 530 ppm (or below a stricter global target of 500 ppm). Therefore, the emission reduction potentials of the different sectors and countries and the role of key technologies are analysed using a model based approach based on the TIMES PanEU model.

Keywords. Energy System modelling, Climate policy, Emission reduction, EU-27.

3.4 Coupled bottom-up and top-down modelling to investigate cooperative climate policies (*Annals of Operations Research*, Submitted).

Authors: M. Labriet et al.

Abstract. In order to assess the cooperation between industrialized and developing countries in the design of a comprehensive worldwide climate policy to limit the global long-term temperature increase to 2◦C, we developed an iterative procedure to link the global technology-rich optimization energy model TIAM and the global general equilibrium model GEMINI-E3. Such a novel coupling methodology combines the precise representation of technology choices and their impact on climate change, and a coherent representation of the welfare gains or losses associated with the techno-economic choices. The assessment of globally and partially cooperative agreements (equivalent to a global Emissions Trading System or to project-based technology cooperation) shows that drastic technology breakthroughs and implementations are required as soon as possible, especially in the larger emitting countries, and in all sectors of the economy; focussing only on the power sector is not sufficient. Moreover, some risk of delocalization of both gas extraction and energy-intensive industries exist

in the case of partial agreements, but they result in a limited carbon leakage thanks to the reduction of oil extraction in all cases.

Keywords. Energy modelling; Coupling Methodology; Bottom-up model; Top-down model; Climate cooperative policy.

3.5 A stochastic control/game approach to the optimal timing of climate policies

(J.A. Filar and A. Haurie, editors, *Handbook on "Uncertainty and Environmental Decision Making"*, *International Series in Operations Research and Management Science*, Springer Verlag, pp. 211-236, 2010).

Authors: O. Bahn, A. Haurie, and R. Malhamé

Abstract. This paper deals with an application of stochastic control or stochastic game methods to the design of optimal timing of climate policies. In the first part, we propose a stochastic control approach for a {\em cost-benefit} model that takes into account the uncertainty on the access to a backstop (clean) technology. In a second part, we show how this model can be extended to a game theoretic framework, assuming non-cooperative behavior of two groups of countries that are affected by climate change related damages induced by their joint greenhouse gas emissions. Finally we discuss the possibility of implementing successive control synthesis cycles preceded by learning cycles concerning climate sensitivity statistics.

3.6 Emission Performance Standards and EU Emission Trading Scheme - modeling uncertainties in policy measures (to be submitted).

Authors: Mikael Odenberger and Filip Johnsson

Abstract. Successful implementation of policy measures for tackling climate change depends on political commitment and long term commitment. In practice, the case seems often to be the opposite, weak political commitment and uncertainty with respect to which policy measures will be implemented and if there will be conflict between several measures. The latter is in focus of this paper which studies possible conflicts between the EU Emission Trading Scheme (EU-ETS) and Emission Performance Standards (EPS), based on a techno-economic energy systems modelling exercise. EPS have from time to time been proposed as a possible additional policy measure to reduce CO2 emissions from European power generation. EPS is in this context defined as emission restrictions on a power plant level, i.e. net CO2 emissions are given fixed limits per unit of power produced in the plant. Introduction of EPS is intended to govern the choice of power plant technology to less carbon intensive alternatives. As an example an EPS level of 350 gCO2/KWh would only allow natural gas fired power plants and, thus, coal plants can only be built once CCS is available. Yet, formal

proposals on how such a policy would be formulated have not been presented by EU authorities, which obviously lead to uncertainty and worries among stakeholders such as those in the utility industry. This paper explores how the European electricity supply system can develop over time up to the year 2050 and how possible introductions of different EPS policies would interplay with the European Emission Trading Scheme (EU-ETS).

The analysis is based on modelling scenarios with the aid of the techno-economic model ELIN (cf. Energy Policy 37, 2009, pp1660–1677) with the objective of finding cost-efficient investment strategies within the electricity supply system. Special emphasis is put on including the influence of the present electricity generation system, considering timing of new investments and technology choices when meeting stringent CO2 reduction targets. Thus, the existing capital stock (power plants) is included in the model through application of a detailed database, the Chalmers Energy Infrastructure Database (cf. Energy Policy 35, 2007, pp3643-3664), providing information on present and planned power plants down to block level (e.g. fuel type, capacity and age structure). This makes the model well suited for assessing scenarios including EPS also on existing power plants. Assuming technical lifetimes for the power plants in the database gives residual capacities remaining over the period studied, which together with new investments meet projected electricity demand. New investment options are aggregated into technology classes (e.g. hard coal condensing power and onshore wind power). The assessment is performed with an EU-27 geographical scope, yet with an individual representation of each member state in the modelling. The analysis includes scenarios with and without inclusion of EPS as well as inclusion of fully integrated markets for electricity, CO2 emission allowances and a joint European effort to meet the targets for renewables.

The results indicate that technology options at hand and efficiency measures provide the means to reduce CO2 emissions from power generation in line with what is required to meet established EU targets for the year 2020 without any introduction of EPS. Introduction of EPS will limit technology options for new investments, and thus lead to increased system cost compared to if the same emission reductions are met by EU-ETS as the only policy measure (possible combined with renewable targets). Furthermore, EPS will increase the dependency on natural gas as a fuel until CCS become commercially available, which can be problematic from a security of supply point of view. Introduction of EPS on existing power plants results in premature retirement in terms of technical lifetimes with the consequence of an intensive replacement period around the year of such EPS introduction. In all, application of EPS in parallel to EU ETS can disturb the carbon market and result in low (or even zero) prices on CO2 in the trading scheme. Yet, experiences show strong local opposition to new coal plants and, thus, in reality it may be difficult to build new coal plants even without the introduction of EPS.

3.7 CCS in the European Electricity Supply System – assessment of national conditions to meet common EU targets (*Energy Procedia*, Elsevier, 2010).

Authors: M. Odenberger, J. Kjärstad, F. Johnsson

Abstract. This paper investigates the role of CO_2 capture and storage (CCS) technologies as part of a portfolio for reducing CO_2 emissions from the European electricity supply system until the year 2050. The EU Commission, gives targets on greenhouse gas emissions for the entire energy system and for the electricity generation system CO_2 emissions are regulated by means of the European Emission Trading Scheme (EU-ETS). Yet, the ability of different EU Member States and regions to facilitate and to benefit from CCS will most likely depend on local conditions in terms of current energy mix, fuel supply chains and distance to suitable storage locations. Thus, the aim with this study is to estimate the contribution from CCS and where such systems should be built. The analysis is based on modelling a scenario, with the aid of a technoeconomic model which is regionalized down to Member State level, finding cost-efficient investment strategies within the electricity supply system until 2050. The modelling is carried out for EU-27 at a member state level with differentiated assumptions on costs and availability of different electricity generation technologies. Special emphasis is put on the transition from the present system to a system which meets stringent CO_2 reduction targets, considering timing of new investments and technology choices. Thus, the existing capital stock (power plants) is included in the model through application of a detailed database, the Chalmers Energy Infrastructure Database, providing information on present and planned power plants (e.g. fuel type, capacity and age structure) down to block level. Assuming technical lifetimes for power plants in the database gives residual capacities remaining over the period studied, which together with new investments have to meet projected electricity demand. The scenario investigated estimates development under the current policy regime inflicted on the European power sector, such as integrated markets for electricity, CO_2 emission targets and trade with emission allowances, a joint European effort to meet targets for renewables as well as indicative targets of implementing efficiency measures to limit growth in electricity demand.
The scenario presented here assumes emission reductions within the electricity sector of 85% by 2050, compared to 1990 emission levels. The results show that in order to meet these goals, significant changes are required in the current infrastructures of the electricity-supply system. The challenge is not due to a lack of technologies – these are available at costs which should not be prohibitive for society and which, indeed, are expected from the EU Emission Trading Scheme (ETS) – but due to the large investment ramp-up required and to fuel-market implications as well as the institutional and logistical challenges (permitting procedures, matching CO_2 sources with sinks and establishing CO_2 transportation systems in-between). In addition, it can be seen that efficiency measures to reduce electricity demand are of great importance to reduce the strain in capacity ramp-up of CCS and renewables. Common targets on CO_2 emission reductions point to differentiated strategy between member states. Thus, regions which currently have high carbon intensity and are located near suitable storage sites will

benefit most from CCS implementation, whereas other regions have large potentials for renewable electricity generation (e.g. coastal areas with high expectations in annual average load hours for wind power). For this reason, this paper provides a European overview of how the aggregate system can evolve under the given assumptions as well as corresponding development in member states which should require building up a large CCS infrastructure.

3.8 Biomass Retrofitting A Natural Gas-Fired Plant To A Hybrid Combined Cycle (HCC) (*Proceedings of ECOS 2009 22nd International Conference on Efficiency, Cost, Optimization*, ABCM Simulation and Environmental Impact of Energy Systems, 2009).

Authors: Erik Pihl, Filip Johsson, Henrik Thunman

Abstract. This work investigates retrofit of a natural gas fired plant for co-firing with biomass. The retrofit is by integration of a solid biomass combustor with the bottoming cycle of a combined cycle gas turbine (CCGT) plant, to form a Hybrid Combined Cycle (HCC). The motivation is the need to find efficient options for substitution of natural gas by biomass to meet the imminent need to reduce CO_2 emissions as well as improve security of supply in the utility power sector, which in some regions is heavily dependent on power generation from rather new CCGT plants. The work is based on process simulations using an existing 600 MW_{fuel} combined heat and power CCGT plant (commissioned 2006) as reference.

It is shown that the HCC retrofit only yields a minor decrease in plant efficiency; electric efficiency (η_e) of 43.3%, compared to 44.4% for natural gas-only in the reference plant (full load and full substitution of supplementary firing corresponding to 39% of natural gas). A HCC with higher biomass-firing capacity and an additional high-pressure condensing turbine can increase the substitution of natural gas to 59% yielding η_e = 40.8% and total efficiency (electricity and heat) of 87.1%, i.e. a larger decrease in efficiency than for 39% substitution. A HCC plant gives in all configurations higher electric efficiency than a corresponding combination of single-fuel stand-alone plants, CCGT for natural gas and steam CHP plants for biomass, with the same share of biomass in the fuel mix.

A simulation representing one year's operation of hybrid and reference options, including part load cases, show that overall efficiencies can be kept at roughly the same levels as in full load.

It is recognized that layout of existing plant, projected level of natural gas substitution and local conditions in fuel supply and energy demand are necessary to consider when assessing the most suitable option for CO_2 abatement by biomass in a gas power plant.

Keywords. Biomass, Energy Efficiency, Modeling, CCGT, District Heating.

3.9 Evaluation of Biomass-based Technologies for Substitution of Natural Gas in a Combined Cycle CHP Plant (to be submitted).

Authors: Erik Pihl, Filip Johnsson, Henrik Thunman

Abstract. This paper presents and evaluates options for substitution of natural gas with biomass in a combined cycle plant (CCGT) with supplementary firing, operated in combined heat and power (CHP) mode. Such options should be of interest, since there have been large investments in CCGT units over the last decades and it is likely that there will be a need to reduce CO2 emissions from these units. The options investigated are indirect atmospheric gasification of biomass to Synthetic Natural Gas (SNG) for firing in the CCGT, biomass firing in a stand-alone boiler (CHP) and integration of a solid fuel combustion unit in a biomass/natural gas hybrid combined cycle. These options are compared to an existing 600 MWfuel CCGT reference plant by means of simulations. The comparison is made quantitatively (thermal efficiencies) and qualitatively (risk and flexibility of the options).
The simulations show that the hybrid scheme will have significantly higher (41.7%/97.9% electric/total) efficiency than both the gasification option (26.0%/91.9% electric/total) and the stand-alone biomass boiler (32.4%/98.6% electric/total). The gasification scheme offers the highest load factor and flexibility (in fuel and energy carrier), but suffers from lower efficiency and higher risks compared to the hybrid scheme. The biomass boiler option is a low-risk technology with high total efficiency, but with lower flexibility than gasification and lower electric performance than the hybrid option. Choice of the most suitable option is dependent on factors such as risk willingness, fuel access and the revenue from selling heat, power and gas. Applying the results on the Gothenburg case study, it is concluded that options based on solid combustion (Bio, BioHyb) are more attractive (due to higher efficiency, lower risks and better compliance with local district heating demand) than a gasifier solution (Gasif). For other energy systems the conclusion may differ, i.e. local conditions should be considered when evaluating various options.

Keywords. Biomass, Gasification, Co-Firing, District Heating, Energy efficiency.

3.10 Highly efficient electricity generation from biomass by integration and hybridization with combined cycle gas turbine (CCGT) plants for natural gas (*Energy*, Elsevier, 2010).

Authors: Erik Pihl, Stefan Heyne, Henrik Thunman, Filip Johnsson

Abstract. Integration/co-firing with existing fossil fuel plants could give near term highly efficient and low cost power production from biomass. This paper presents a techno-economical analysis on options for integrating biomass thermal conversion (optimized for local resources ~50 MW_{th}) with existing combined cycle gas turbine

(CCGT) power plants (800-1400 MW_{th}). Options include hybrid combined cycles (HCC), indirect gasification of biomass and simple cycle biomass steam plants which are simulated using the software Ebsilon Professional and Aspen Plus. Levelized cost of electricity (LCoE) is calculated with cost functions derived from power plant data. Results show that the integrated HCC configurations (fully-fired) show significantly higher efficiency (40-41%, LHV) than a stand-alone steam plant (35.5%); roughly half of the efficiency (2.4 %-points) is due to more efficient fuel drying. Because of higher investment costs, HCC options have cost advantages over stand-alone options at high biomass fuel prices (>25 EUR/MWh) or low discount rates (<5%). Gasification options show even higher efficiency (46-50%), and the lowest LCoE for the options studied for fuel costs exceeding 10 EUR/MWh. It can be concluded that clear efficiency improvements and possible cost reductions can be reached by integration of biomass with CCGT power plants compared to stand-alone plants.

3.11 Comparative assessment of future power generation technologies based on carbon price development (*Renewable & Sustainable Energy Reviews*, Vol. 14, Iss 4, pp. 1283-1292, Elsevier, 2010).

Authors: Dalia Streimikiene

Abstract. The long-term assessment of new electricity generation was performed for various long-run policy scenarios taking into account 2 main criteria: private costs and external GHG emission costs. Such policy oriented power generation technologies assessment based on carbon price and private costs of technologies can provide information on the most attractive future electricity generation technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.
Analysis of life cycle GHG emissions and private costs of the main future electricity generation technologies performed in this paper indicated that biomass technologies except large scale straw combustion technologies followed by nuclear have the lowest life cycle GHG emission. Biomass IGCC with CO2 capture has even negative life cycle GHG emissions. The cheapest future electricity generation technologies in terms of private costs in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. As the electricity generation technologies having the lowest life cycle GHG emissions are not the cheapest one in terms of private costs the ranking of technologies in terms of competitiveness highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and climate change mitigation targets.

Keywords. Energy technologies assessment, carbon price.

3.12 Comparative assessment of transport technologies based on carbon price development (*2010 IEW papers*, 2010).

Authors: Dalia Streimikiene

Abstract. The aim of the paper is to assess energy technologies in power and transport sectors. The main tasks are to develop the framework for comparative assessment of energy technologies based on future carbon prices imposed on economy by post-Kyoto climate change mitigation regimes. The assessment framework allows comparing transport technologies in terms of their environmental and economic impacts. The main indicators selected for technologies assessment are: private costs and external costs of GHG emissions. The ranking of transport technologies based on total social costs allows to identify the most perspective technologies in future taking into account international climate change mitigation constraints and to promote these technologies by policy tools. The main results presented in this paper were obtained during EU financed Framework 7 project "PLANETS" dealing with probabilistic long-term assessment of new energy technology scenarios.

Keywords. Energy technologies, comparative assessment, carbon price.

3.13 Monitoring sustainable energy development (*Environmental Impact Assessments*, pp. 1-54, Nova Science Publisher, 2009).

Authors: Dalia Streimikiene

Abstract. The aim of the chapter "Monitoring sustainable energy development in the country" is to analyse various tools for monitoring sustainable energy development in the country and to develop new tools seeking to enhance synergies between energy and environmental policies. The system of indicators and integrated indices will be developed for monitoring sustainability of energy sector development and applied on Lithuania. The main tasks of the chapter are the following:

- To define the main characteristics of sustainable energy development;
- To describe EU sustainable energy policy priorities;
- To analyse monitoring tools, such as indicators systems, integrated indices, multi-criteria analysis tools for monitoring implementation of sustainable development strategies;
- To develop comprehensive system of indicators and integrated indices for monitoring sustainability of energy sector development;
- To present Lithuanian case study on implementation of developed monitoring tools for sustainable energy development and sustainability assessment of policies;
- To develop recommendations for energy and environmental policies harmonization and synergies for Lithuania.

Keywords. Sustainable energy development monitoring, multi-criteria analysis.

3.14 Assessment of energy technologies based on carbon price developments (*Proceedings of International Conference "Convergence of science & engineering in education and research, a global perspective in the new millennium*", 22-24 April 2010,Bangalore, 2010).

Authors: Dalia Streimikiene

- **Abstract.** The aim of the paper is to assess energy technologies in power and transport sectors. The main tasks are to develop the framework for comparative assessment of energy technologies based on future carbon prices imposed on economy by post-Kyoto climate change mitigation regimes. The assessment framework allows to compare power generation and transport technologies in terms of their environmental and economic impacts. The main indicators selected for technologies assessment are: private costs and external costs of GHG emissions. The ranking of energy technologies based on total social costs allows to identify the most perspective technologies in future taking into account international climate change mitigation constraints and to promote these technologies by policy tools. The main results presented in this paper were obtained during EU financed Framework 7 project "PLANETS" dealing with probabilistic long-term assessment of new energy technology scenarios.

Keywords. Energy technologies, comparative assessment, carbon price.

3.15 Effectiveness of CCS with time-dependent CO_2 leakage (*Energy Procedia,* vol. 1, issue 1, pp. 4977-4984, Elsevier, 2009).

Authors: B.C.C. van der Zwaan and R. Gerlagh

Abstract. The effectiveness of CCS, i.e. its emission abatement potential in relation to the possibility of leakage of CO_2 from geological reservoirs once this greenhouse gas has been stored artificially underground, will be among the main determinants of whether CCS can significantly contribute to a deep cut in global CO_2 emissions. This paper presents an analysis of the economic and climatic implications of the large-scale use of CCS for reaching a stringent climate change control target, when geological CO_2 leakage is accounted for. The natural scientific uncertainties regarding the rates of possible leakage of CO_2 from geological reservoirs are likely to remain large for a long time to come. We present a concise analytical inspection, as well as an analysis with a more detailed integrated assessment model, proffering insight into the economics of geological CO_2 storage and leakage. CO_2 leakage lowers the value of CCS as climate

mitigation option below the prevailing level of the CO_2 tax. We therefore employ a definition for the effectiveness of temporary carbon storage as the net present value of the total stream of avoided emissions. We calculate the effectiveness of CCS under two leakage models (an exponential model with a constant seepage rate and a two-layer model with a bell-shaped time-dependent seepage rate) and with different assumptions regarding (1) the carbon tax growth rate relative to the interest rate and (2) the average CO_2 storage life-time. We introduce the expression for the effectiveness of CCS in a top-down integrated assessment model that represents three main CO_2 emission reduction options: energy savings, a carbon to non-carbon (renewable) energy transition and the use of CCS. We find CCS to remain a valuable option even with CO_2 leakage of a few %/yr, well above the maximum seepage rates that we think are likely from a geo-scientific point of view.

3.16 Uncertainty and Environmental Decision Making: A Handbook of Research and Best Practice (J.A. Filar and A. Haurie (eds.), Springer's International Series in Operations Research & Management Science, Springer, 2009. 11, 2009).

As an activity partially supported by the PLANETS project, this book has been edited by J. Filar and A. Haurie, in the Springer's International Series in Operations Research & Management Science on the topic Uncertainty and Environmental Decision Making. Several chapters, [61, 7, 107, 10], in this book are directly related to the topic of PLANETS workpackage 6 on stochastic scenarios. In particular in "Or/ms and environmental decision making under uncertainty" (pag. 1-50), Filar and Haurie discuss in general terms OR/MS and Environmental Decision Making under Uncertainty and present the sources of uncertainty in these modeling approaches.

3.17 PLANETS policy brief

A policy brief describing the results and recommendations of the PLANETS research project was prepared and distributed at the end of the project with the aim of ensuring a wider dissemination. These document is also available on the PLANETS website (http://www.feem-project.net/planets/).