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PLANETS

Probabilistic Long-Term Assessment of New Energy Technology Scenarios

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PLANETS – Probabilistic Long-Term Assessment of New Energy Technology Scenarios
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Report on "Policy Implications for the EU"

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1. Summary of recommendations

by Massimo Tavoni (FEEM) and Bob van der Zwaan (ECN)

This policy brief describes the results and recommendations of PLANETS (www.feem-project.net/planets), a research project funded by the European Commission under the Seventh Framework Programme with the scope of devising robust scenarios for the evolution of low carbon energy technologies over the next few decades. A suite of six energy-economy-climate modelling groups analysed the implications of several climate policies under a wide set of assumptions about national commitments and the use of international carbon offsets. The work under the PLANETS project focused in particular on uncertainties, regarding both the future evolution of climate policies and the prospects of key carbon mitigation technologies. The modelling efforts were complemented with techno-economic assessments of a number of specific mitigation options, among which Carbon dioxide Capture and Storage (CCS) and bio-energy.

1.1 Interim emission targets matter for the economics of long-term climate stabilisation.

A shift towards binding climate stabilisation can occur along different pathways. The PLANETS project analysed ten possible climate control scenarios with six different integrated assessment models. These scenarios combined long-term climate stabilisation targets of 500 and 530 ppm-equivalent (ppm-e) – consistent with long-term equilibrium temperature increases of 2.3 and 2.5°C respectively, under a central value for the climate sensitivity – with different strategies regarding how to achieve these targets. Immediate and fully cooperative action starting from 2012 was compared with “second-best” scenarios characterised by different regional emission quotas.

Results indicate that emission reductions targets for 2050 are relevant for the economics of long-term climate stabilisation. Several models find that multiple scenarios with a 500 ppm-e climate target are unreachable, in particular those in which some regions aim at initially mild reductions followed by more drastic reductions after 2050. Postponing abatement makes it impossible, or at least considerably more costly, to achieve climate stabilisation.

1.2. The global costs associated with stringent climate policy are manageable, but are very sensitive to the specific temperature target and the speed of action.

Table 1 shows that the global cost of achieving a climate target of 530 ppm-e is not negligible. On average, however, this cost stays below 1-2% of Gross World Product, with wide variations across models. The 500 ppm-e target is much more difficult to attain. In most cases it is achievable, but at a significantly higher cost than with the laxer target and on the condition that abatement actions start at full speed from 2012. This target becomes infeasible, even with early action, if high economic growth materialises. In contrast, when second best quota systems are assumed, the target is reachable only in the case of optimistic technological perspectives. The global cost associated with these scenarios is much higher than for the laxer target, especially after 2050.

Greenhouse Gas Concentration Target	Equilibrium Temperature Increase	Global Macro-economic Costs	
		2030	2050
530 ppm-e	2.5 ºC	0.3%÷2.6%	0.7%÷6%
500 ppm-e	2.3 ºC	1%÷3%	2%÷>8%

Table 1. Global costs across models for two climate stabilisation targets under a first best assumption of immediate participation.

This result indicates that even for climate policy less ambitious than a 2 degree Celsius target, the rapid creation of a global coalition is a prerequisite for success. In other words, a course of deep global emission reductions needs to be initiated as early as possible, since initially mild emission reductions followed by more drastic mitigation after 2050 could make climate stabilisation infeasible or exceedingly costly. A relatively small extra temperature reduction of 0.2°C implies disproportionate additional global costs, or even potential infeasibility, due to the high non-linearity of abatement costs.

1.3. The design of an effective and engaging global climate deal should consider regional heterogeneities.

As an alternative to immediate and global participation, the PLANETS project considered two different second best quota systems. In both these quota scenarios the developed world (i.e. OECD) takes immediate stringent emission reduction action, while the developing world postpones its abatement efforts by at least several decades. Both quota systems imply an overall global reduction of greenhouse gas emissions in 2050 of about 28% with respect to emissions in 2005. One of the core differences between the two quota systems is that in one case the OECD reduces its emissions down to a level of 20%, while in the other it decreases these emissions to a deeper floor of 10% with respect to 2005 emissions. These different mitigation levels balance out with differences in emission reductions achieved by the three other groups of countries considered: energy-exporting nations, developing Asia and the rest of the world.

The two quota systems generate significantly different results, especially in terms of regional costs. The OECD and developing Asia see their costs more than double when switching from one quota system to the other. The costs per GDP for the EU are lower than those for the OECD as a whole. This means that the EU is better positioned to achieve larger emission reductions than the more recent faster-growing countries of the OECD.

Other regions also show varying costs depending on the quota allocation implemented. The revenues resulting from permit trading typically have a large impact on both macro-economic and regional costs. Developing countries (except those in the category of energy-exporting nations) usually play the role of permit sellers in all scenarios. They can therefore gain large benefits from an international carbon market, especially in more stringent climate scenarios characterised by a rapidly increasing carbon price.

Energy-exporting countries probably experience large costs incurred as a result of high expected baseline emissions and reduced revenues from the oil market. This factor is likely to affect to some extent the success of, and the costs associated with, global climate policy. The price of oil (and behind it the behaviour of OPEC) may affect the possibility of ensuring climate stabilisation, but it is not expected to be among the main determinants.

1.4. Moderate restrictions on the use of international carbon trading might induce modest global economic penalties.

The unrestricted access to emission credits from third countries (that is, international offsets) maximises economic efficiency, but it may reduce domestic abatement efforts and adversely affect the stimulation of innovation in low carbon energy technology. For this and other reasons, some countries consider restricting the purchase of emission credits from third countries. Most of the findings of the PLANETS project indicate that the global costs of emission control are only modestly affected by a moderate limit on emissions trading, as demonstrated in Figure 1.

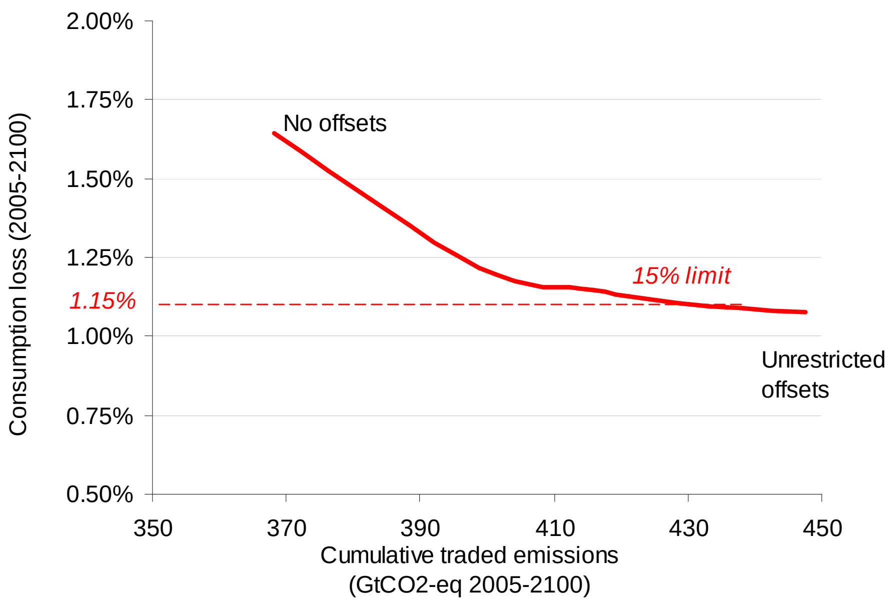

Figure 1. Global costs for various levels of restrictions on the use of international offsets (based on results from the WITCH model).

The adoption of a global trading limit, however, can have quite a significant impact on the abatement costs incurred in individual regions. When trade is restricted, permit-buying regions undertake more emission reductions domestically, which calls for a more pervasive economic effort. On the other hand, trade restrictions induce more innovation in low carbon technologies, with beneficial international spill-overs of knowledge and positive repercussions on energy security.

1.5 Achieving climate stabilisation requires a diverse and dynamic portfolio of mitigation options that initially favours technologies that can be integrated in existing energy systems.

The policy scenarios analysed under the PLANETS project indicate that, to minimise overall climate compliance costs, the most cost-efficient solution exploits a broad set of different mitigation options. This set accounts for the different time scales associated with the deployment of different energy technologies. Based on economic considerations and environmental concerns for climate change, our models suggest that this set relies consistently on a combination of nuclear power, renewables, and CCS applied to fossil fuels and biomass. Energy saving has also proven to be an important strategy, both in the supply sector and in the end-use sector, especially when the scope for technological substitution is limited.

Technologies that can be integrated in existing energy systems, and do not require drastic changes in consumer behaviour, generally possess a clear advantage. For example, given the growing capacity of coal-based power, co-firing biomass with coal is an important near-term mitigation option. When not only economic arguments but also social and environmental aspects are considered, renewables (predominantly solar, wind and hydroelectric power) are among the top-ranking greenhouse gas emission reduction technologies. Nuclear energy is penalised by certain economic features as well as aspects of social acceptability, but it becomes a particularly valuable option when a carbon price internalises the environmental externality of climate change. Nuclear power is thus an important mitigation option for stringent climate policy.

1.6 CCS could be an important mitigation technology in the medium term, but making it work requires a balanced mixture of policy instruments.

The results of the PLANETS project confirm the growing belief in the policy arena that CCS has the potential to materialise large emission reductions, especially in the mid-term. All PLANETS models consider CCS – either in combination with the combustion of fossil fuels or biomass – an effective and efficient mitigation technology, especially in the mid-term until 2050. As such, CCS is found to be a bridging technology. Indeed, CCS could be an appropriate mitigation alternative until the next generation of carbon-free technologies becomes competitive, because it fits the current energy system without the necessity for major infrastructure changes. In the long term after 2050, CCS is expected to become less important in reducing greenhouse gas emissions, since it is not an entirely non-emitting energy technology, whereas renewable and nuclear power plants in essence are.

The PLANETS models vary significantly in projecting the nature of the future role of CCS, as shown in Table 2. Models that foresee a large role for energy savings suggest a relatively small deployment of CCS in the power sector. Models that determine large increases in the use of electricity, however, employ such increases as a means to implement CCS on a large scale.

ETSAP-TIAM	WITCH	GEMINI-E3	DEMETER	TIAM-ECN
75%	11%	19%	38%	43%

Table 2. Percentage of global emission reductions achieved via CCS in 2050 in a representative scenario.

The application of CCS to power plants is still in an early demonstration phase, and various technical and economic implications remain uncertain. The timing of CCS implementation is strictly linked to the possibility of ramping up the entire chain of capture, transport and storage of CO_2 in a coordinated way. Scaling challenges may constitute a sizeable obstacle to the widespread diffusion of CCS technology. The ability of society to establish large transportation networks and orchestrate storage activity internationally will depend on many factors, including institutional and political ones. Surmounting the corresponding hurdles may not prove straightforward, even while from a technical point of view CCS today appears a proven technology.

Climate policy is shown to be a key determinant of the market share that CCS may obtain. Policy stability proves to be fundamental in determining the choice of investments in CCS projects. Modelling results of the PLANETS project suggest that CCS is more sensitive to climate policy uncertainty than to technological cost uncertainty, because CCS is competitive only if the climate externality is internalised with a credible and stable carbon price.

A mix of policy instruments could contribute to reducing both policy and technology uncertainty for CCS. While emission performance standards could shield the deployment of CCS from policy uncertainty, there are economic arguments against such standards. CCS technology should not be fully exempted from carbon taxes, not only because it is not a fully carbon-free technology, but also because one cannot yet exclude the risk of CO_2 leaking from the underground, even though such leaks would occur in a far distant future.

2. Summary of the Findings of WP5

by Richard Loulou (KANLO)

2.1. Introduction and objectives

The research done in WP5 is a comparative analysis of ten climate scenarios, resulting from two contrasted long term climate targets and five strategies to achieve these targets. These ten scenarios were analysed using five different global models plus one regional model of the European Union. The models' input assumptions were only superficially harmonized in order to assume similar global population growth rates and Gross World Product growth rate, entailing similar global GHG emissions. Otherwise, each model retained its own detailed techno-economic assumptions. Table 3 contains a list of the six models. Tables 4 and 5 succinctly describe the 10 policy scenarios. Table 6 indicates which scenarios were successfully run by each model.

Model	Brief description
DEMETER	Global single region CGE model. Learning and leakage of underground CO2 storage. Very long term.
WITCH	Global multi-regional CGE. Representation of R&D investments with endogenous technological breakthrough. 2100 horizon
GEMINI-E3	Global multi-regional CGE. 2050 horizon.
ETSAP-TIAM	Global multi-regional partial equilibrium model with elastic demands, and detailed technological description. 2100 horizon
TIAMEC	Global multi-regional partial equilibrium model with elastic demands, and detailed technological description. 2100 horizon
PEM	Multi-country European partial equilibrium model with elastic demands, and detailed technological description. 2050 horizon

Table 3. The six models in PLANETS.

Climate target Policy	Forcing in 2100 not to exceed 3.2 W/m2	Forcing at all times not to exceed 3.5 W/m2
First Best (global cooperation starting in 2012)	FB-3p2	FB-3p5
Second Best with Quota System I	SC1-3p2	SC1-3p5

Second Best with Quota System II	SC2-3p2	SC2-3p5
Second Best with Quota System I and Offsets limited to 20% of reductions	VAR1-3p2	VAR1-3p5
Second Best with Quota System II and Offsets limited to 20% of reductions	VAR2-3p2	VAR2-3p5

Table 4. The 10 policies in PLANETS.

	STARTING DATE OF QUOTAS	**Quota System SC1** **QUOTAS in 2050** **As % of 2005 emissions** **(reduction in brackets)**	**Quota system SC2** **QUOTAS in 2050** **As % of 2005 emissions** **(reduction in brackets)**
OECD	2015	20% (reduction=80%)	10% (reduction=90%)
ENERGY EXPORTING - EEX	2025	50% (reduction=50%)	100% (reduction=0%)
DEVELOPING ASIA - DevASIA	2025	125% (increase of 25%)	100% (reduction=0%)
ROW	2025	155% (increase of 55%)	200% (increase of 100%)
WORLD		**72% (reduction of 28%)**	**73% (reduction of 27%)**

Table 5. The two sets of quotas used for the second best scenarios.

	ETSAP-TIAM	WITCH	GEMINI-E3	DEMETER	TIAMEC	PEM
Reference	Y	Y	Y	Y	Y	Y
FB-3p2	Y	Y	Y**	Y	Y	Y
SC1-3p2	Y	Y	INFEASIBLE	INFEASIBLE	INFEASIBLE	Same as SC1-3p5
SC2-3p2	Y	Y	INFEASIBLE	INFEASIBLE as SC1-3p2	INFEASIBLE	Same as SC2-3p5
VAR1-3P2	Y	Y	INFEASIBLE	INFEASIBLE as SC1-3p2	INFEASIBLE	Same as SC1-3p5
VAR2-3P2	Y	Y	INFEASIBLE	INFEASIBLE as SC1-3p2	INFEASIBLE	Same as SC2-3p5
FB-3p5	Y	Y	Y	Y	Y	Y
SC1-3p5	Y	Y	Y	Y	Y	Y
SC2-3p5	Y	Y	Y	Same as SC1-3p5	Y	Same as SC1-3p5
VAR1-3P5	Y	Y	Y	Same as SC1-3p5	Y	Y
VAR2-3P5	Y	Y	Y	Same as SC1-3p5	Y	Same VAR1-3p5

Table 6. The set of runs done by each model.

** In this run, GEMINI-E3 found the problem infeasible in year 2050 only.

Broadly speaking, one may expect two types of insights from the comparison of results from different models: those derived from results where the models broadly *agree*, and those where they *differ*. Actions on which models -in spite of their intrinsic differences, agree, are deemed *robust* (and thus confidence inspiring). When models disagree, the analyst must be careful to distinguish between two different types of model divergence: the one that comes from differing assumptions on the models' input data, and the one coming from the differing natures ("philosophy") of the models. In some cases, the two types of divergence are hard to separate.

Regarding input data, we have only made a loose attempt at harmonizing the global growth assumptions of population and economic output at a very aggregate level (in addition, of course, the models are all calibrated to a recent year). Even so, one model (DEMETER) assumes a faster growth of emissions than other models. Generally, input data assumptions differ in many important ways, concerning regional socioeconomic drivers, technology availability and characteristics, economic demands, and resource potentials. The important point is that when data differ but the models' paradigms are similar (e.g. ETSAP-TIAM and TIAMEC), the divergence of results may be safely attributed to input assumptions.

When input assumptions are similar but models' paradigms are contrasted, the analyst must exercise his skill in order to discover the insights hidden in the contrasted results. Modelling paradigms differ in important ways, and these differences are more difficult to quantify, while often extra interesting, since they refer to distinct methodological approaches. The three models that are based on technological choice (usually named bottom-up) follow the same paradigm: the agents in the energy system construct a technological portfolio so as to reach the climate target at minimum social cost (global total surplus). The choice is very finely delineated by a long list of technology characteristics (technical and economic) that in the end determine the relative competitiveness of each individual technology. The three other models are loosely grouped in the top-down category, inasmuch as the agents in the energy system do not in general (there are exceptions in some sectors) choose specific technologies by comparing their detailed characteristics, but rather switch from one fuel to another via production functions that allow fuel switching by means of elasticities of substitution. The typical production function allows each agent to choose a point in a continuum of mixes of capital, energy, and sometimes materials and labor. But there are variants; for instance, in the WITCH model, a "breakthrough" technology may emerge more or less rapidly if certain R&D investment decisions are made (endogenously) by the model. Additionally, WITCH allows Learning by Doing in the electricity sector.

Confronted with such variance in data and modelling approaches, what can the analyst expect from the comparison of results? Our view is that *the variety of models and data may well represent the lack of perfect knowledge on how the economy really functions*. In this view, the 'cloud' of model results is considered as representing a true range of uncertainty, and thus provides a range within which the future lies. This view may be altered if the analyst superimposes his own beliefs in order to qualify certain results, eliminate outliers, etc.

Insights of type I: A clear and unambiguous insight is gained whenever certain actions are selected by all or most models even though they operate under different assumptions or paradigms. These actions are then deemed to be robust.

Insights of type II: a second benefit of multi-modelling exists even when the models produce very different, perhaps contradictory results. In such cases, the analyst is alerted to the possibility that certain unforeseen strategies might be relevant *if certain conditions prevail*. An example is the role of electricity production in the climate scenarios: two models show a decrease in electricity production (and use), the other three indicate an increase. In both cases, the model's choices are perfectly justified and traceable to the assumptions and/or to the model's 'philosophy'. Such situations do not provide clear cut suggestions of robust actions, but nevertheless enlarge the field of vision of the analyst by indicating *actions that might become desirable under certain conditions (contingent actions).*

In what follows, we review these two types of insight as they are revealed by the results of the runs. We also indicate, whenever pertinent, what issues have not been resolved by the project.

2.2. Main issues raised by this work and at least partially answered

The following is a list of the main issues raised and at least partially resolved by our study.

- How feasible are the targets? What are the welfare losses attached to them? How useful is early cooperation? (i.e. how detrimental are delays in acting ?)
- Are the two issues of equitable sharing and of global efficiency decoupled or inextricably linked?
- What is the impact of a 20% restriction on emission trading?
- What early actions appear to be robust for achieving climate targets?
- What actions are contingent on still uncertain determinants?

We briefly summarize our answers to these issues in the rest of this section.

2.2.1. Are the targets attainable?

All models agree on the feasibility of achieving the 3.5 W/m2 forcing target, under either quota system studied (as well as in the absence of a quota system). This is an important finding.

As observed in our study, this target entails a change in mean global surface temperature (MGST) increase of roughly 2.2 °C in 2100 under an average climate sensitivity of 3°C. This temperature change is a little short of the often quoted 2°C "acceptable" threshold. The global cost of achieving this target is not negligible, but stays within 1% of the Gross World Product until 2040. After 2050, cost per GWP is larger but stays within 2% of GWP in most models.

The 3.2 W/m2 forcing target is much more difficult to attain. Four out of five models find that target achievable but at much higher costs than the laxer target, and on the condition that abatement actions start at full speed from 2012. The fifth model finds this target infeasible even with early action, but the reason is clearly traced to the assumption of a much higher economic growth in that model. In contrast, when either quota system is assumed, only two models find the target reachable, and the global cost attached to it is again much higher than for the laxer target, especially after 2050, when global cost reaches up to 7% of GWP.

The clear conclusion is that if the 3.2 target is to be reached, the rapid creation of a global climate coalition is a requisite condition to success. To say this differently, the world had better start on a course of deep emission reductions as early as possible, rather than aim at mild reductions initially, followed by more drastic reductions after 2050.

We note that this target implies a change in MGST of 2°C in 2100 under an average climate Sensitivity of 3°C. It is thus interesting and useful to observe that a relatively "small" difference of 0.2°C in 2100 means very large additional global costs, or even potential infeasibility.

2.2.2. Comparing the two quota systems

The two quota systems studied in this research are regionally very contrasted but globally equivalent, since they are both globally compatible with the long term 3.5 target. However, the two quota systems have very different impacts on regional costs, and this is exclusively due to the costs and revenues derived from permit trading. OECD and Developing Asia see their costs under SC2 increase more than twofold compared to SC1, and the situation is reversed for the other two country groups.

- The study clearly indicates that the additional 10% reduction required by SC2 is very costly to achieve by OECD. Note also that OECD incurs generally larger costs than other regions (except EEX) even when expressed as % of GDP, as one would expect from the very tight quotas (i.e. large reductions) in both SC1 and SC2. EU has slightly smaller costs per GDP that the entire OECD, showing once more that EU is better positioned to make large reductions than the faster growing other OECD countries.

- For energy exporters the situation is reversed, since SC2 represents a relaxation of that region's reduction commitment. For SC1, this region incurs the largest costs per GDP (by far) of all regions, reflecting the expectations of high emission growth in their baseline and the reduced revenues of the oil market. Energy exporting countries are net buyers in the SC1 scenario, but net sellers in the SC2 scenario.

- For Developing Asia just like for OECD, SC2 is a more demanding scenario than SC1. This is borne out by the study. In fact, under SC1, one model indicates large *negative* costs for that region, quite certainly due to large revenues from selling emission permits at a higher CO2 price than the other model. According to the results, in the SC1 scenario, Developing Asia may supply up to between 40% and 90% of the carbon market, leaving the rest of the permit supply to ROW, the second major supplier.

- The Rest of the World has negative costs under SC2, due to a large amount of permits sold. Under SC1, the cost for that region remains under 1% of its GDP.

- We note that under either quota system, the costs per GDP continue to show significant differences between regions. In particular, Energy exporting countries continue to incur costs that are up to 3 times the cost per GDP of the other groups, even in the more favorable SC2 system of quotas. Additional investigation of fair quota systems would therefore be a desirable further research topic.

- As mentioned above, the two quota systems are globally equivalent in terms of global costs. But our work also shows that choosing between the two quota systems has a negligible impact on the *timing* of the global reductions. Still more interestingly, *even regional reductions are quasi unaffected by which one of the two quota systems is selected*. In other words, the same abatement actions are taken *in each region* irrespective of which of the two quota systems is used. The explanation of this observation resides in the fact that emission trading strongly determines where (and how much) emission reductions are made, irrespective of "who pays".

2.2.3. The impact of a 20% limit on permit trading

Most results indicate that the overall global cost of emission control is only mildly affected if a limit on emissions trading of 20% is imposed on each group of countries until 2050. This encouraging result means that the vast majority of emission reductions may happen inside each country grouping, with little impact on global cost.

However, the adoption of the trading limit does have significant impacts on abatement cost in individual regions. OECD and Energy exporting countries see a rather large increase in their cost, while Developing Asia and the Rest of the World see a corresponding decrease of their abatement costs (when costs and revenues from permit trading are accounted for).

2.2.4. Some robust actions

There is unanimity in all models to recommend strong energy savings and large amounts of renewables (biomass, wind, solar) and nuclear, when climate targets are imposed. In fact, energy savings are the preferred strategy chosen by T-D models, along with adoption of renewable power plants, and modest amounts of Carbon Capture and Storage in the electric power sector.

B-U models also choose to implement energy savings in end-use sectors, and electricity from renewable sources and nuclear, but their strategy also includes a larger amount of CCS. All models consider CCS as an effective and efficient technology in the mid-term, but tend to reduce recourse to CCS in the very long term (post 2050). This is congruent with the fact that CCS is not a truly non-emitting technology, whereas renewable and nuclear power plants are.

2.3. Diverging results (contingent insights)

One rather important difference occurs with respect to the role played by electricity in final energy. The B-U models recommend large increases in the use (and production) of electricity, which therefore replaces other end-use fuels (whether fossil, renewable, or conservation). In effect, B-U models use the increased recourse to electricity as a means of implementing large amounts of CCS. On the contrary, T-D models indicate less electricity in climate scenarios than in the reference case, a strategy that is coherent with the fact that these models implement larger energy savings than their B-U counterparts.

These two contrasted strategies constitute a true difference in approach. Both are coherent with the respective paradigms of the two classes of model, as well as with the assumptions made on the potential for CCS.

The contingent conclusion emerging from such diverging recommendations is that the CCS technology must be studied in more depth and detail before major decisions are taken on its massive implementation. If CCS proves to be relatively cheap and abundant, it will deserve a truly large role in GHG abatement. If not, energy savings, nuclear, and renewable would be used more heavily, at least for the next 3 or 4 decades.

3. Summary of the Findings of WP4

by Filip Johnsson et al. (CHALMERS)

3.1. Introduction

Below is a summary of policy implications from the technology assessment work carried out in PLANETS (in WP4 – Technology Assessment II). The assessment work concerns possible contribution from near- and medium-term technological options for climate change mitigation. The focus has been on CO2 Capture and Storage (CCS) technologies and biomass conversion technologies. This, since these are subject to intensive research and development and since these two groups of technologies are associated with different uncertainties and also face controversies in the public debate.

The CCS assessment covers capture, transport and storage. As for biomass technologies these include biomass supply systems and biomass conversion technologies.

The policy implications given below is for decision makers as well as for energy systems modellers to consider when formulating inputs to modelling and when formulating scenarios, including modelling of uncertainties on future contribution from CCS and biomass to climate change mitigation.

3.2. CO_2 Capture and Storage - CCS

CO_2 Capture and Storage[1] (CCS) has gained increased interest during the last decade. This is mainly due to that: 1) large storage capacity for carbon dioxide is available at many sites around the world, 2) it is unlikely that the carbon dioxide will leak out, and 3) the CCS technology is potentially cost-effective, obviously assuming that a price is established for carbon dioxide emissions.

CCS is now generally believed to contribute to large cuts in emissions of CO2 until year 2050 and beyond. Yet, CCS has not been applied at scale and depends on successful development of the capture technologies as well as successful ramp-up of the transportation and storage infrastructure of the captured CO2. A key short term uncertainty is the progress of the demonstration phase of CCS which is envisioned to take place from now and until around year 2020. Thus, large scale commercialization of CCS is generally expected to take place from year 2020 and onwards, i.e. in 10 years from now (2010). Consequently, this puts a strong pressure on getting a

[1] Often also referred to as "Carbon Capture and Storage".

successful research, demonstration and commercialization process in place over the coming decade, as well as on efficient planning and build up of a CCS transport and storage infrastructure. If successfully implemented CCS cannot only contribute to reducing (or almost eliminating) CO2 emissions from coal fired electricity generation (and other large emission point sources), but also enhance security of supply by allowing the use of domestic fuel resources such as lignite and coal. Potential downsides are possible lack of public support in some regions and the risk of long term lock-in in fossil fuelled technologies. In summary, the following overall policy relevant conclusions can be drawn:

- CCS is generally assumed to take a significant share of CO2 reductions from the stationary energy system (mainly electricity generation) from 2020 and onwards.

- Roll out costs for CCS are estimated to be in the order of 25 €/ton CO2 avoided (capture, transport and storage), *i.e.* less than the cost level expected from the European Emission Trading Scheme (EU-ETS) from year 2020 and on.

- The different capture technologies proposed are similar in estimated costs but differ in complexity.

- Different capture technologies are likely to fit different niche markets (local conditions, including fuel properties) rather than there will be one “winner technology”.

- Storage potential is large, a fact which is one of the major motivations for the large interest in CCS.

- First successful large scale demonstration of the chain capture, transport and storage will have a high symbolic value and once successfully implemented, it is likely that it will be much more difficult to get acceptance for building coal plants without CCS.

- Successful implementation of CCS fits with increased electrification of transport sector. Thus, policies for transport sector and stationary sector must be integrated.

- Successful commercialization of CCS is likely to make it easier to get regions which are highly dependent on fossil fuels to agree on binding commitments on climate targets.

CCS is expected in the first instance to be cost-effective in large (around 1,000 megawatts) coal fired power plants that are running in baseload. Especially lignite (“brown coal”) is a low cost fuel and in Europe this fuel is often burned in high efficient power plants with state-of-the-art flue gas cleaning resulting in low emissions of harmful products such as nitrogen and sulphur oxides, but of course with high emissions of carbon dioxide. Typically, such power plants may have an electric efficiency of around 43% but this could be increased to some 48%, still using available technology. Future plants may reach 50%. Considering typical energy penalty from carbon capture of 7 to 8% (in absolute terms) would result in that first commercial application of CCS plants around 2020 may very well have an electric efficiency similar to that of current coal plants without capture (>40%).

There are, however, a number of uncertainties on the near future prospects of CCS as well as there are several challenges which must be overcome in order to ensure successful commercialization of CCS around 2020 and beyond. Above all, clear and long term policy measures, which secure a high enough cost to emit CO2 is the most crucial condition which must be fulfilled to ensure that CCS is developed, demonstrated and commercialized over the next decade.

From the technology assessment made in this work it can be concluded that at present it seems *unlikely* that *CCS will significantly contribute to climate change mitigation before 2025*. If a significant CCS contribution is to take place already in 2025, it requires from now (2010) on, a massive action to develop CCS globally and to find integrated ways to build up a transport and storage infrastructure. An obvious condition is successful large scale demonstration of CCS within the next five years or so. The following can be concluded in this context:

- A key issue to get CCS commercialized is that an integrated transportation and storage infrastructure is established in a timely manner (planning must be commenced within a few years) and market regimes must be found (e.g. public private partnerships).

- Most storage estimates available build on rather rough estimates and site specific investigations are required in order to arrive at actual storage capacity. Ways/policies to stimulate site specific investigations of storage capacity must be found.

- Although the above mentioned estimates of roll-out costs seems attractive, initial costs during first years after commercialization[2] may be significantly higher. Thus, it is important to find CCS support schemes and concerted actions in building up a CCS infrastructure so as to minimize the time before roll-out costs are reached.

[2] Commercialization is here used for a CCS system which is built at large scale and exhibits satisfactory operation. Another – stricter – definition would be that CCS is not considered to be commercialized until the cost for entire chain capture-transport-storage is lower than the corresponding cost to emit CO2 (e.g. as imposed by the European Emission Trading Scheme).

- It is of high importance to ensure that the large scale demonstration projects planned will be successfully implemented. For EU it is important that the six projects which have recently received economic support from the EU recovery funds will be successfully carried through, and that experiences can be efficiently used by projects to follow.

- A “Plan B” should be developed as backup in case of delayed CCS introduction (or failure of CCS). An obvious challenge is such as case is how the international community should handle the large resources of fossil fuels (which then obviously cannot be used to the same extent as if CCS was available or in case of CCS failure, has to be phased out completely over s few decades).

- There is a significant need for investment in base-load electricity generation before 2020, i.e. before CCS is available. This calls for long term and stable policy measures with respect to CO2 (and GHG) emission control so as utilities already now can plan for the introduction of CCS.

- For EU, investments during the period until CCS is available may enhance the dependence on natural gas for electricity generation.

- Possible introduction of Emission Performance Standards may conflict EU-ETS (e.g. result in zero prices on emission permits).

- CCS is likely to face local opposition (all early demonstration projects have faced opposition) and ways to handle this must be developed.

In summary, successful commercialization of CCS seems crucial to mitigate climate change, especially considering the likelihood of making countries and regions which are heavily dependent on fossil fuels (especially coal) to agree on strict CO2 emission reductions. The main challenges for CCS is most probably in reaching the estimated roll-out costs around or slightly after, year 2020. Clear and long term climate change mitigation policy is important in order to send clear signals to the market that efforts spent on developing CCS will be rewarded in the long run.

3.3. Biomass conversion technologies

Bioenergy is the only renewable energy form that inherently generates carbon-based fuels, which is the basis for much of present-day energy technology. This makes biomass very suitable for use in both heat and power production and in the transport sector, where it is presently the major renewable alternative to gasoline and diesel. Cost efficient introduction of biomass must take advantage of the existing energy infrastructure such as in various co-firing schemes for electricity generation. Successful implementation of biomass technologies will also depend on the biomass supply infrastructure. Overall, it can be concluded that:

- There are a large number of possibilities to convert biomass to different products (electricity, transportation fuels and combinations of these).

- There are considerable variations in fuel as well as in investment costs both between the groups of conversion technologies and within each group of technology.

- Different technologies have different requirements of scale to maintain efficiency – a challenge is to find options which can maintain high efficiency also at reasonable plant size (i.e. reasonable biomass flows since biomass availability will be a limiting factor in most regions).

- The existing energy infrastructure could be used as an advantage with respect to that it could facilitate a low risk and low cost option for establish a market for biomass.

- Cost effective and near term options for biomass based climate change mitigation exist in stationary energy sector and these can also have energy security benefits:

    - Biofuels can replace oil for heat/power.

    - Bio-electricity expansion can reduce gas import dependency.

Yet, biomass is associated with several uncertainties and challenges as well as associated with issues which are not straight forward. In all, the following can be concluded:

- There is an uncertainty in the climate benefit of biomass.

- Techno-economic performance and commercial availability of options for second generation biofuels are subject to substantial uncertainties.

- Relative competitiveness of available and future biofuel options depends not only on their ”stand-alone” techno-economic performance but also on how they fit into the existing energy infrastructure such as:

    - Pipelines allowing transport/distribution of gaseous/liquid biomass.

    - Blending opportunities with existing fuels (e.g., ethanol vs. butanol).

    - Availability and competition for surplus heat from other energy/industrial activities.

    - Availability of heat sinks (e.g., district heating systems).

- Development of biofuels for transport can be based on European as well as imported biofuels.
    - EU biofuels promotion has to some extent been counterproductive from the perspective of supply side development for second generation biofuels.
    - International biomass/biofuel trade is developing fast in terms of volumes traded as well as institutional aspects including policy regimes.
- There is a large variation in the climate change mitigation benefit of substituting fossil fuels with solid/liquid/gaseous biofuels.
    - Direct GHG emissions depends on inputs in feedstock production and conversion (and also on methodology used for quantification).
    - Indirect GHG emissions (notably due to induced land use change) can change the carbon mitigation benefit dramatically.
    - Choice of time horizon for evaluation of climate change mitigation benefit is highly influential on the net climate change mitigation benefit of bioenergy projects.
    - Tendency to use rather short time horizons disqualifies some biofuel options that provide relatively high climate change mitigation benefit on the longer term.
    - Some studies indicate that bioenergy can make an important contribution to reaching longer term stabilization targets despite significant near term GHG emissions connected to bioenergy expansion.
- Preferred (cost effectiveness, energy security considerations) biomass use for energy depends on performance of bioenergy options but also on how other non-bio energy options develop.
    - Transport sector: fuel cell vehicles, electric vehicles, plug-in hybrids.
    - Stationary sector: CCS, co-firing with higher shares of biomass.
- On the longer term, lignocellulosic biomass appears to be the major preferred feedstock regardless of end use sector.

- Land Use Change in agriculture towards production of more lignocellulosic plants can provide significant environmental benefits in addition to climate change mitigation.
    - Increased soil C and improved soil productivity
    - Reduced water and wind erosion and reduced leakage of nutrients and other chemic.
- It is important to stay open for the possibility that – despite near term GHG emissions connected to bionergy expansion – bioenergy may give an important contribution to climate change mitigation on the longer term.
    - Burn less coal to save emission space for putting a bioenergy system in place that can provide renewable fuels for society on the longer term.
- An important possibility for EU should be to stimulate supply side development for lignocellulosic biomass based on developing near term markets in stationary energy sector.
- Important to capture synergy possibilities associated with biomass use in order to serve several environmental objectives.
- Development of decision support systems for bioenergy needs prioritization between different environment/development objectives.

As for biomass co-firing it is shown that this can offer a low cost and low risk option for introducing biomass at scale in the energy system. An important question which needs to be answered is to what extent biomass demand for co-firing could bridge to lignocellulose based bioenergy such as second generation biofuels by stimulating a substantial development of lignocellulosic supply systems. Development of biofuel preparation technologies can allow for higher biofuel shares in the fuel mix.

With respect to land use options for climate change mitigation and the uncertainty in climate benefits of bioenergy a first assumption should be that biomass that substitutes for fossil fuels (especially coal) in heat and electricity generation in general provides larger and less costly CO2 emissions reduction per unit of biomass than substituting biofuels for gasoline or diesel in transport. Thus, other options should be compared with biomass for heat and electricity. The implications of drastically reduced mitigation benefit due to land use change emissions should be taken into consideration. Also alternative use of land to produce carbon sinks instead of bioenergy should be considered.

There is a large span in costs as well as in thermal efficiencies between various biomass conversion technologies. Also, the different processes yield different size (installed capacity) in order to reach cost effectiveness. Thus, it is problematic to compare biomass conversion processes if comparison is only made on a cost basis since the different processes are suitable for different markets. Comparing processes which can only be implemented on a smaller scale with the large base load plants for CCS (as well as for co-firing biomass in such plants) points to a general problem in having costs as the main parameter for comparison of different technologies since technologies do not compete on the same markets. This is a conclusion important for analysis which is to be used as basis for decision makers.

4. Summary of the Findings of WP3

by Dalia Streimikiene (LEI)

4.1. Introduction

The aim of the WP3 is to perform sustainability assessment of future energy technologies taking into account EU sustainable energy policy targets. The main tasks of WP3 is: 1) to review EU policies and to systematize their targets, to develop indicators framework for energy technologies sustainability assessment and to apply this framework for sustainability assessment of future electricity generation technologies in EU; 2) to carry out policy oriented assessment of energy technologies in electricity and transport sectors based on the carbon prices developed in the various policy scenarios analysed in the Planets project.

4.2. Sustainability Assessment of Energy Technologies

The main EU policy documents and directives which have impact on sustainable energy development are directives promoting energy efficiency and use of renewable energy sources, directives implementing greenhouse gas mitigation and atmospheric pollution reduction policies and other policy documents and strategies targeting energy sector. The set of 13 indicators for sustainability assessment of electricity generation technologies was selected based on EU energy and environmental policy analysis and literature review (Table 7).

Acronym	Indicator	Unit	Description and information sources
		Economic	
PR COST	Private costs	EURcnt/kWh	Average Levelised Generating Costs (ALLGC methods). EUSUSTEL project.
AVAILAB	Average availability factor	%	Average availability factor (%) is based on typical load factors. EUSUSTEL and NEEDS project.
SECURE	Security of supply	Scores (1 to 5)	Qualitative indicator represents by long-term independence from foreign energy source. NEEDS project.
GRID COST	Costs of grid connection	Scores (1 to 5)	Qualitative indicator to assess the risk that a certain technology will include high cost for grid connection as private costs of electricity generation do not include costs related to grid connection. The higher the score the higher risks of high cost for grid connection. CASES project.
PEAK LOAD	Peak load response	Scores (0 to 5)	Peak-load response **is** a qualitative indicator which reflects the technology-specific ability to respond swiftly to large temporal variations in demand. NEEDS, PSI data.
		Environmental	
CO2eq	GHG emissions	kg/kWh	Life cycle emissions of GHG emissions in kg (CO2-eq.)/kWh. The indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity. NEEDS, EUSUSTEL, CASES .
ENV	Environmental external costs	EURcnt/kWh	The environmental external costs in EURcnt/kWh is the estimates for damage to ecosystems due to emissions to air, soil and water of particles, gases, the formation of ozone and the emissions of metals. NEEDS and CASES projects.

RADIO	Radionuclide external costs	EURcnt/kWh	The external health costs in EURcnt/kWh provide the estimates for damages to health due to emissions to air, soil and water of particles, gases, the formation of ozone, and emissions of metals. CASES project.
HEALTH	Human health impact	EURcnt/kWh	Radionuclides external costs in EURcnt/kWh are external costs estimates for damages to health due to emissions of life cycle radionuclides including indirect use of nuclear electricity in the production of other technologies. NEEDS
Social			
EMPL	Technology-specific job opportunities	Person-year/kWh	Technology specific job opportunities in person-year/kWh indicator are based on the average amount of labour used to produce a unit of electricity. It does not give the total number of persons employed (some jobs might be part-time), or the quality of the jobs. The PSI database.
FOOD	Food safety risk	(Score 1 to 5)	Food safety risk is qualitative indicator for qualitative assessment of the risk that using biomass fuels will put stress on food supply safety and food prices. CASES project.
ACC PAST	Fatal accidents from the past experience	Fatalities/kWh	Fatal accidents from past experience in fatalities/kWye indicator represents the risk of fatal accident using the frequency of occurrence o a severe accident in the past and the number of fatalities involved in previous accidents. PSI database.
ACC FUT	Severe accidents perceived in future	(Score 1 to 5)	Severe accidents perceived in the future is qualitative indicator represents qualitative assessment of risk of a severe accidents in the future. The higher the score the more people perceive that accident will happen. This indicator is similar to risk aversion. NEEDS.

Table 7. Indicators for long-term sustainability assessment of electricity generation technologies.

The equal treatment of the three dimensions environment, economy and society is not without controversy. Therefore the sustainability assessment of energy technologies requires a MCDA approach. The integrated sustainability assessment indicators for each technology were calculated by summing weighted indices of all indicators. If decrease of indicator (for example, external costs or private costs) has positive impact on sustainable development the indices of such indicators are integrated as inverted indices. The sensitivity analysis by changing criteria weights according several scenarios will be applied. In one scenario the weights will be equally distributed between economic, environmental and social components. In the economically focused scenario, the economic criteria is given a weighting of 50%, while the environmental and social criteria have a weighting of 25% each. The other scenarios will be defined in an analogous manner by running environmentally and socially focused scenarios.

In environmentally focussed scenario the best technologies having the lowest score of integrated sustainability assessment indicator are renewable and the worst technologies are mainly coal based. Ranking of electricity generation technologies in economically oriented scenario indicates that the best technologies according to economic criteria are natural gas and hydro energy technologies. The technologies having the highest score of integrated sustainability indicator or being the worst according to sustainability criteria are fuel cells based technologies and mature oil and natural gas technologies. The ranking of electricity generation technologies according to socially foccused scenario suggest that the best technologies having the lowest score in this scenario are solar and hydro and the worst – lignite and other mature heavy oil and coal technologies.

4.3. Comparative Assessment of Energy Technologies based on Carbon Price Development

Because the focus of Planets project is on climate change mitigation scenarios, the most important part of WP3 is the assessment of energy technologies accounting for the future carbon prices described by various policy scenarios developed during Planets project. For the policy-oriented assessment of energy technologies, WP3 included both private and external costs of GHG emissions. The life cycle GHG emissions indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity or ride of 1 vehicle km. In order to integrate long-term technology assessments with modelling results, the carbon price obtained by various policy scenarios runs will be used to calculate the GHG emission externalities of selected energy technologies in power and transport sectors. These two sectors were selected based on IPCC methodology, as they are the major sources of GHG emissions. Ten policy scenarios runs were performed by 4 energy models for 5 regions: 2 first best scenarios FB-3p2 and FB-3p5 setting the alternative climate targets after 2050: 3.2 W/m^2 and 3.5 W/m2; 4 second best policy scenarios with alternative climate targets and two sets of commitments for world regions; 4 variant scenarios which are analogous to second best policy scenarios but with restriction on GHG emission trading.

4.4. Life-cycle GHG Emissions and Private Costs of Future Electricity Generation Technologies

The ranges of life cycle GHG emissions for power and heat generation technologies obtained from literature review are shown in Table 8.

Fuel or energy type	Direct CO_2 emissions from combustion		Life cycle CO_2 emissions		Average value, of life cycle GHG emissions, kg/MWh
	kg/GJ	kg/MWh	kg/GJ	kg/MWh	
Nuclear	2.5÷30.3	9÷110	2.8÷35.9	10÷130	65
Oil	126.9÷300.7	460÷1090	137.9÷331.0	500÷1200	850
Natural gas	96.6÷179.31	350÷650	110.3÷215.2	400÷780	590
Hard coal	193.1÷262.1	700÷950	206.9÷344.8	750÷1250	1000
Hard coal IGCC with CO_2 capture	*52.4÷60.7*	*190÷220*	*38.6÷46.9*	*140÷170*	*155*
Large scale wood chips combustion	-	-	21.0÷23.0	76.0÷83.3	79.6
Large scale wood chips gasification	-	-	6.0÷8.0	21.6÷29.0	25.3
Large scale biomass IGCC with CO_2 capture	*-139.4÷-143.5*	*-505÷-520*	*-35.9÷-41.4*	*-130÷-150*	*-140*
Large scale straw combustion	-	-	62.0÷70.0	223.2÷252.0	237.6
Biomass (wood chips) CHP large scale	-	-	6÷10	21.6÷36.0	28.8

Biomass (wood chips gasification) CHP small scale	-	-	3÷6	10.8÷21.6	16.2

Table 8. Life cycle GHG emissions of the main energy technologies in power sector.

As one can see from information provided in Table 8, biomass wood chips gasification technologies have the lowest life cycle GHG emissions followed by wood chips CHP large scale. Hard coal technologies have the highest life cycle GHG emissions followed by oil and natural gas technologies. Hard coal IGCC with CO_2 capture technologies have quite low life cycle GHG emission comparable even with Large scale wood chips gasification technologies. Nuclear technologies have lower life cycle GHG emission than some biomass technologies for example large scale straw combustion technologies and large scale wood chips combustion technologies. Biomass technologies with CO_2 capture have negative life cycle GHG emissions. Especially high negative GHG emissions occur during combustion processes of Biomass IGCC with CO_2 capture.

The private costs in EURcnt/kWh are based on the Average Levelised Generating Costs (ALLGC) methodology. The ranges of values were selected from literature review (Table 9).

Fuel or energy type	Costs, EUR/MWh		Average private costs, EUR/MWh
	Min	Max	
Nuclear	24	42	33
Oil	79	100	90
Natural gas	53	60	57
Hard coal	21	44	33
Hard coal IGCC with CO_2 capture	40	43	42
Large scale wood chips combustion	35	38	37
Large scale wood chips gasification	42	49	46

Large scale biomass IGCC with CO_2 capture	57	60	59
Large scale straw combustion	44	48	46
Biomass (wood chips) CHP large scale	37	60	49
Biomass (wood chips gasification) CHP small scale	37	60	49

Table 9. Long-term private costs of power generation technologies, EUR/MWh.

As one can see from information provided in Table 9, the cheapest technologies 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. In terms of private costs, the energy technologies having the lowest life cycle GHG emissions are neither the most expensive nor the cheapest one. Therefore the ranking of technologies in terms of competitiveness would highly depend on the carbon price implied by various policy scenarios that simulate specific GHG emission reduction.

4.5. Ranking of Future Electricity Generation Technologies based on Carbon Price Developments

In order to compare electricity generation technologies on the basis of carbon prices, two scenarios were selected: first best and second best scenarios. The ranking of 11 main future electricity generation technologies for 2020 and 2050 based on external costs of GHG emissions is the same for 2020 and 2050 as the same life cycle GHG emissions were applied for technologies assessment in all time frames. The most attractive technologies on the basis of external costs of GHG emissions in 2020 are: biomass IGCC with CO_2 capture, small scale biomass CHP (wood chips gasification), large scale wood chips gasification, large scale biomass CHP (wood chips combustion), nuclear, large scale wood chips combustion, hard coal IGCC with CO_2 capture. Less attractive technologies are: large scale straw combustion, natural gas, oil and hard coal. Fig. 2 and Fig. 3 present the range and average values of total (private and external costs of GHG emissions) costs of electricity generation technologies in 2020 and 2050, respectively, according to the first best policy scenario FB-3p2.

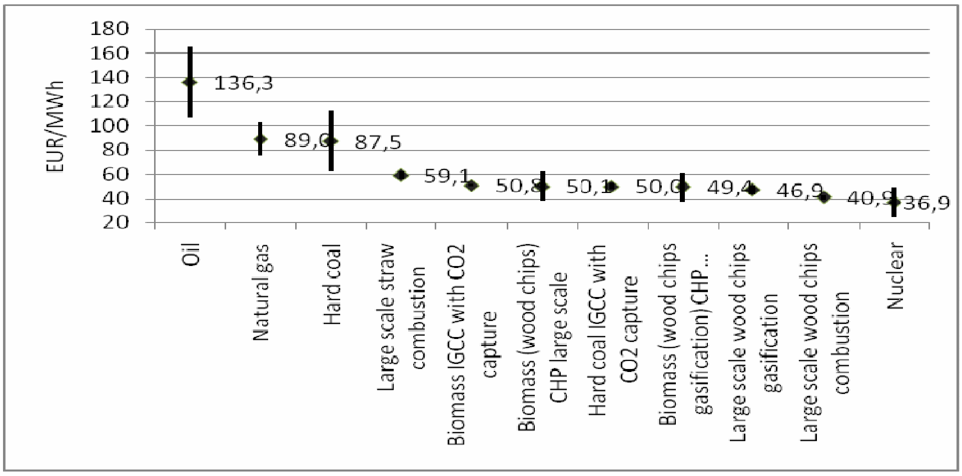

Fig. 2. The range of social costs of electricity generation in 2020 according the first best policy scenario FB-3p2.

As one can see from Fig. 2, because of large uncertainties related with life cycle GHG emission and private costs of power generation technologies, the ranking of electricity generation technologies is quite complicated. However, Fig. 2 clearly shows that the best electricity generation option in 2020 is nuclear followed by large scale wood chips combustion and other biomass technologies. Oil based technologies are the least attractive followed by natural gas and coal technologies. The most expensive biomass based technology in 2020 is large scale straw combustion technology. Hard coal with CO_2 capture technology is ranked in the same order like most biomass based technologies including biomass with CO_2 capture.

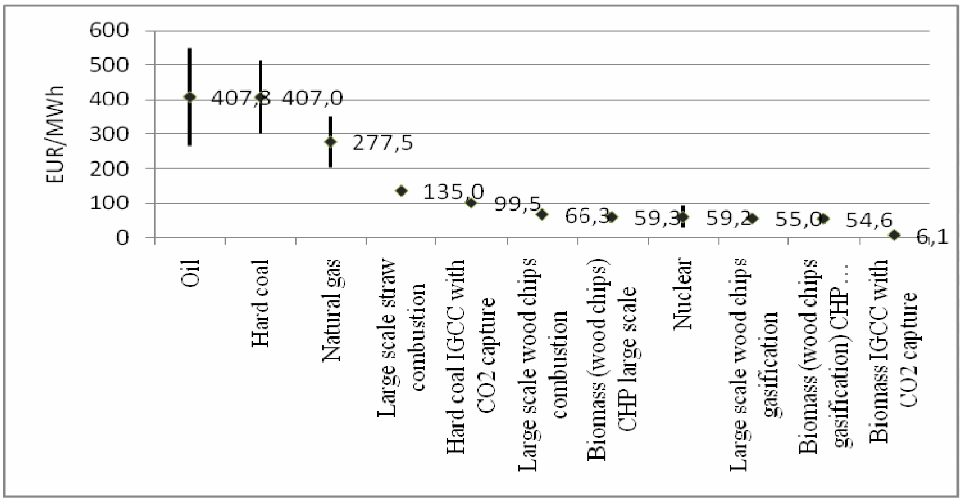

Fig. 3. The range of social costs of electricity generation in 2050 according the first best policy scenario FB-3p2.

In 2050 the ranking of electricity generation technologies based on the same scenario (Fig. 3) provides completeley different results. The most competetive technology in 2050 is biomass ICGG with CO_2 capture, followed by other large scale biomass technologies and nuclear. Oil, hard coal and natural gas based technologies are the least competetive technologies in 2050. Hard coal with CO_2 capture is less attractive technology comparing with variety of biomass based technologies except large scale straw combustion.

Comparison of Fig. 2 and 3 indicates that technology ranking in 2020 and 2050 is quite different because the higher carbon prices in 2050 affects the external cost of GHG emissions. The most competitive technologies according total costs (private and external costs of GHG emissions) in 2020 are: nuclear, large scale wood chips combustion, large scale wood chips gasification, biomass (wood chips gasification) CHP small scale, hard coal IGCC with CO_2 capture, biomass (wood chips) CHP large scale and biomass IGCC with CO_2 capture. Total costs of these first ranked technologies are quite similar except for nuclear. The less attractive technologies are: large scale straw combustion, hard coal, natural gas and oil. In 2050, the ranking of the same electricity generation technologies based on total costs is: biomass IGCC with CO_2 capture, biomass (wood chips gasification) CHP small scale, large scale wood chips gasification, nuclear, biomass wood chips CHP large scale, large scale wood chips combustion, hard coal IGCC with CO_2 capture, large scale straw combustion, natural gas, hard coal and oil.

The ranking of electricity generation technologies according external costs of GHG emissions and total costs (private and external) costs is similar for less strict first best policy scenarios that impose a 3.5 W/m^2 target instead of 3.2 W/m^2.

A different ranking emerges when using the carbon price from a second best policy scenario. Because the carbon price is lower, for some technologies external costs of GHG emissions do not overweight the private costs. When ranked using the carbon price from the second best scenario SC1-3p2, the most competetive technology is still nuclear, followed by large scale wood chips combustion technologies. The hard coal based technologies are ranked in the same order because of the low carbon price in 2020 and private costs of hard coal based technologies overweight the impact of external GHG emission costs. In 2020, because of quite high private costs, biomass IGCC with CO_2 capture technologies are less competetive compared to the first best scenario. Like in the first best scenario, the most expensive technologies are oil, hard coal and natural gas based technologies. In 2050, the most competitive electricity generation technology is biomass IGCC with CO2 capture, like in the first best scenario. Nuclear is now ranked as second best technology.

To summarize, the most expensive technology in terms of total costs for most policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear and in 2050 – biomass IGCC with CO_2 capture. Biomass IGCC with CO_2 capture is the most competitive in technologies assessment based on total GHG emission costs. The hard coal, oil and natural gas technologies are among the most expensive for all policy scenarios and all time frames. In 2050, because of the high carbon prices in all scenarios, natural gas technologies are more competitive. In 2020 coal technologies are more competitive than natural gas technologies because private costs outweigh external costs of GHG emissions. In the ranking of technologies based on external costs of GHG emissions, the coal technologies are the last attractive one. The ranking of biomass technologies based on total costs is different for specific scenarios and time frame and it depends on the carbon price. Very high prices make more competitive technologies having low life cycle GHG emission such as biomass IGCC with CO_2 capture, biomass wood chips gasification and biomass CHPs technologies, although in terms of private costs these technologies are more expensive than other biomass technologies. Hard coal with CO_2 capture technologies are ranked in the middle and in 2050 have similar total costs as large scale straw combustion technologies.

4.6. Life-cycle GHG Emissions and Private Costs of Transport Technologies

The range of life cycle GHG emissions of transport technologies in g/vehicle km were obtained from literature review (Table 10). Fuel GHG intensity is the key factor which represents the net lifecycle emissions impact associated with the consumption of a unit of fuel. Sometimes termed a fuel's "carbon footprint," it can be expressed in units of grams of carbon dioxide-equivalent per megajoule (gCO_2 eq/MJ) of energy delivered to vehicles or other transportation equipment. Fuel GHG intensity is but one factor among many that contribute to transportation emissions. For our assessment of transport technologies GHG life cycle and direct GHG emissions from combustion will be evaluated in g CO_2 per vehicle km. Conversion of GHG emission data from g CO_2 /l to g CO_2/vehicle km for various fuels is presented in Table 10 as well.

Fuel	CO_2 **emissions on combustion**				**Life cycle GHG emissions,** CO_2 **eq**					Average life cycle GHG emissions g/vehicle km
	g/litre	kg/gal	g/MJ	g/mile at 4.5 MJ/mile	g/litre	kg/gal	g/MJ	g/mile at 4.5 MJ/mile[3]	g/vehicle km[4]	

[3] 4.5 MJ/mile is equivalent to 32.5 mpg for a petrol car or 36.4 mpg for a diesel car. However, this makes no allowance for differences in combustion efficiency between different engine designs. For example, diesel engines run at higher compression ratio than petrol engines and therefore are typically more efficient (fewer MJ per mile).

[4] To convert miles per gallon of a particular fuel to grams of CO_2 per km divide the figure for g/litre of CO_2 (either directly from combustion or lifecycle) by the mpg (miles per gallon) figure multiplied by 0.354 (to convert to km/litre): g/km = (g/l)/(mpg x 0.354) = (g/l x 2.825)/mpg

Petrol	2328	10.6	72.8	328	2600	11.8	81-110	366-495	227.4-307.6	268
Diesel	2614	11.9	72.6	327	3128	14.2	87-90	391-405	243.0-251.7	247
Bioethanol from sugar beet	1503	6.8	71.6	322	724	3.3	37-43	166.5-193.5	103.5-120.2	112
Bioethanol from wheat	1503	6.8	71.6	322	511	2.3	27-31	121.5-139.5	75.5-86.7	81
Biodiesel from rapeseed	2486	11.3	75.3	338	1334	6.1	39-43	175.5-193.5	109.1-120.2	115
Biodiesel from waste vegetable oil	2486	11.3	75.3	338	437	2.0	11-15	49.5-67.5	30.8-41.9	36

Table 10. Life cycle GHG emissions of transport technologies.

As one can see from information provided in Table 11 biodiesel from waste vegetable oil has the lowest life cycle GHG emission followed by bioethanol from wheat. Petrol based transport technologies have the highest life cycle GHG emissions followed by diesel based transport technologies. The range of current and long-term private costs of transport technologies were evaluated in EURcnt/vehicle km based on literature review (Table 11). The price of gasoline and diesel is based on cost of crude oil c.$50/barrel (FOB Gulf cost). These costs for biofuels vary widely depending on location for existing bioethanol and biodiesel technologies.

Fuel	Private costs					Average private costs, EURcnt/ vehicle km
	EURcnt/ litre	Energy density MJ/litre	EURcnt/MJ	EURcnt/mile at 4.5 MJ/vehicle mile	EURcnt/ vehicle km	
Petrol	27.6-47.3	32	0.86-1.08	3.87-4.86	2.41-3.02	2.72
Diesel	27.6-47.3	36	0.77-1.31	3.47-5.90	2.16-3.67	2.92
Bioethanol from	47.3-63.0	21	2.25-3.0	10.13-13.50	6.30-8.39	7.35

sugar beet						
Bioethanol from wheat	55.1-74.8	21	2.62-3.56	11.79-16.02	7.33-9.96	8.65
Biodiesel from rapeseed	31.5-43.3	33	0.95-1.31	4.28-5.90	2.66-3.67	3.17
Biodiesel from waste vegetable oil	55.1-78.8	33	1.67-2.39	7.52-10.80	4.67-6.71	5.69

Table 11. Current private and long costs of transport fuel technologies, EURcnt/vehicle km.

As one can see from information provided in Table 11 the most expensive in terms of fuel costs are bioethanol technologies and the cheapest are transport technologies based on petrol and diesel. Therefore the transport technologies having lowest life cycle GHG emission are among the most expensive terms of fuel costs.

It is important to stress that the ranking of energy technologies based on costs (private, external and total) points to a general problem in having costs as the main parameter for comparison of different technologies since these energy technologies do not compete on the same markets. For example, biomass technologies show a large span in costs and efficiencies and different processes yield different installed capacities. Therefore, it is problematic to compare such processes if comparison is only made on cost basis since the different processes are suitable for different markets. However comparison of different energy technologies based on total costs and carbon price enables to develop some important policy recommendations, if appropriate interpretation of results is provided.

4.7. Ranking of Transport Technologies based on Carbon Price

Transport technologies were compared based on external costs and total costs in 2020 and 2050 for the same scenarios. The most competetive transport technologies based on external GHG costs are technologies having the lowest life cycle GHG emissions, i. e. biodiesel from waste vegetable oil based technologies followed by bioethanol from wheat and from sugar beet based technologies. In Fig. 4 and Fig. 5 the range of total costs and average total costs of transport technologies is provided in 2020 and 2050, respectively, according the first best scenario FB-3p2.

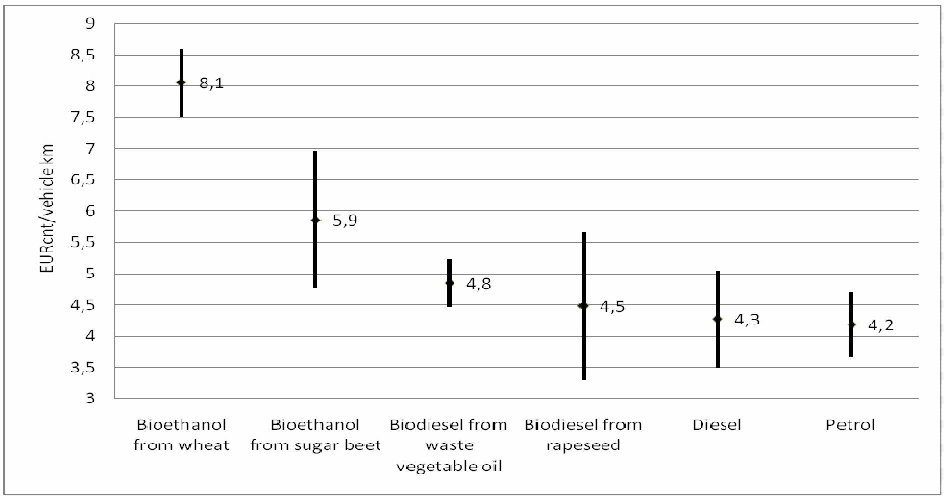

Fig. 4. The average and range of total costs of transport technologies in 2020 according FB-3p2 scenario.

As one can see from Fig. 4, even taking into account wide range of total costs of transport technologies, petrol and diesel fuel based technologies are the most competetive in 2020, as carbon price and external costs of GHG emissions do not outweigh fuel price differences in transport technologies assessment. In 2020, biomass based technologies are more expensive, compared to conventional transport technologies.

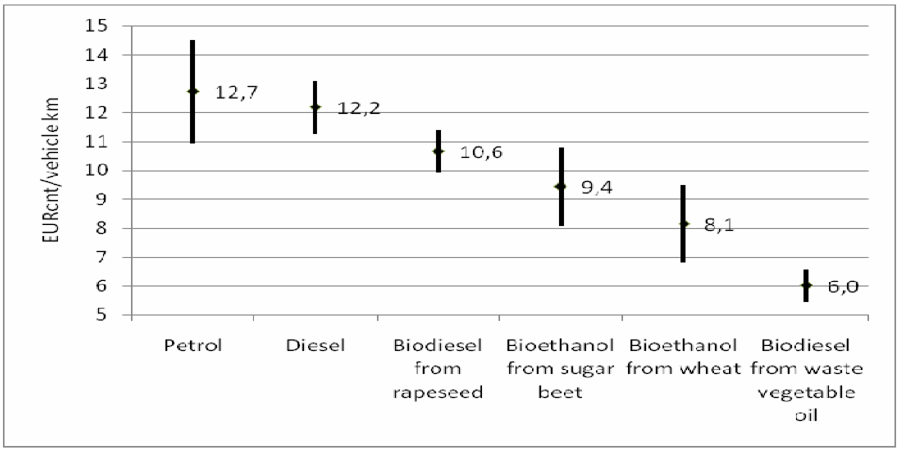

Fig. 5. The average and range of total costs of transport technologies in 2050 according FB-3p2 scenario.

However, as one can see from Fig. 5, the high carbon price in 2050 that would emerge in a first best policy scenario makes transport technologies based on biofuels more competetive than those based on fossil fuels.

Because of the high carbon price in 2050, the petrol and diesel based transport technologies are ranked as the least attractive in this year, although in 2020 they are ranked as the most competetive. At the same time biodiesel from waste wegetable and bioethanol from wheat based transport technologies are the most competitive.

Using the carbon price from second best scenarios, the most expensive technologies in 2050 remain those based on conventional fuels while the most competetive ones are those based on biofuels. However, because the carbon price in second best scenarios is lower than in the first best, the most expensive technology is bioethanol from wheat. The carbon price is not high enough to outweigh the high costs of fuels.

In 2050, in the second best policy scenarios, the carbon price is almost half (178 EUR/tCO2 eq and 170 EUR/tCO2eq) than in the first best scenario (375 EUR/tCO2 eq). Therefore, using second best carbon prices provides very different ranking of transport technologies, compared to the first best scenario. In 2020 the most competetive transport technologies are those based on petrol and diesel, like in the case of first best scenario. However, the least attractive transport technololgies are those based on bioethanol from wheat.

Though in year 2020 carbon prices in first best scenario are significantly higher (55 EUR/tCO2) than in second best scenarios (12 EUR/tCO2 eq in SC1-3p2 and 9 EUR/tCO2eq in SC2-3p2) the ranking of transport technologies in 2020 is very similar for all scenarios. The higher carbon price in the first best policy scenario is still too low to outweigh the impact of private fuel costs.

The most competetive transport technologies in 2020 for all policy scenarios are those based on petrol. The least competetive are those based on bioetanol from wheat. In 2050, the most competetive transport technologies for all scenarios are those based on bioethanol from waste vegetbale oil and the least competetive transport are bioethanol from wheat, excpet in the case FB-3p2. In this scenario, bioethanol from wheat is ranked among the most competitive technologies because of the high carbon price in 2050.

5. Summary of the Findings of WP6

by Frédéric Babonneau and Alain Haurie (ORDECSYS)

5.1 General considerations on the modeling of uncertainty

In conformity with the workplan of PLANETS we have devised an ensemble of probabilistic and robust scenarios for the evolution of the energy system in a climate regime. These scenarios have been produced using three categories of models and four different approaches to deal with uncertainty in the scenario design. The first type of model, represented by WITCH and DEMETER, consists of an optimal economic growth model à la Ramsey, with a climate module and a relatively detailed description of the energy production system. The second class of models consists of bottom-up technology rich models of the MARKAL/TIMES and TIAM families. These models use the paradigm of partial equilibrium to produce globally coherent development scenarios for the energy system under long term environmental constraints. Finally the last type of model is the computable general economic equilibrium model GEMINI-E3. The different approaches to deal with uncertainty in the scenario design are (i) Dynamic Programming, (ii) Stochastic Programming, (iii) Robust Optimization and (iv) Parametric Programming and Monte-Carlo simulations.

Among the various sources of uncertainty concerning the deployment of new climate friendly energy technologies we have focussed on those affecting Carbon Capture and Sequestration or Storage (CCS). Concerning the uncertainty on climate change we have focussed on the Climate Sensitivity (Cs) parameter. Dynamic programming has been used to find R&D investment and abatement policies under stochastic technological and climate science progress. Stochastic programming has been used to deal with uncertainty concerning Climate sensitivity and CCS availability and efficiency. Robust optimization has been used in the TIAM model to model the uncertainty concerning the energy supply channels into Europe. When using Monte-Carlo simulation with GEMINI-E3 we have taken into consideration simultaneously several sources of uncertainty about economic growth, energy prices, climate sensitivity and factor substitution in the production functions.

The production of probabilistic or robust scenarios to deal with uncertainty concerning climate and techno-economic dynamics is inherently a very difficult task. When one uses a dynamic optimization paradigm, the introduction of uncertainty in the form of a stochastic process describing, for example, the temperature change triggered by GHG concentration, the price of oil or the evolution of technological progress, will generally create the famous “curse of dimensionality", where the size of the problem becomes so large that numerical tractability is lost. This phenomenon seriously limits the possibility to implement Dynamic programming in large scale models as indicated in the example fully developed in this research which used a reduced size economic growth model with three “state" variables: the “dirty" and “clean" capital stocks and the GHG concentration. For larger size economic growth models like WITCH and DEMETER, the use of Stochastic Programming permitted the consideration of "uncontrolled" uncertainties (i.e. uncertainties with probability laws not affected by the decisions taken by the agents) in multiregion and thus multi-state economic growth models. The same method of stochastic programming allows the modelers to introduce uncertainty concerning the severity of the environmental (climate) targets in detailed bottom-up models. In all these applications the description of uncertainty has been reduced to a rather simple event tree with a limited number of sample scenarios. An alternative to stochastic programming has been proposed and demonstrated on two bottom-up model formulations. It is called "Robust Optimization" as it tackles directly the construction of robust decision policies without going through probabilistic considerations. The method is presented on a relatively simple bottom-up energy/environment model and its links with the "Chance-constrained programming" approach are described. It is also shown how robust optimization and stochastic programming can be mixed in some models. The robust Optimization methodology is also applied to a TIAM model to study the impact of uncertainty in the capacity of the energy supply channels. The study confirms that Robust Optimization is easy to implement and leads to numerically tractable formulations, even on a large model like TIAM. This shows that Robust Optimization has a potential for further applications in the search for robust energy scenarios.

When everything else fails one can always explore the field of model responses when one varies one or several parameters. Parametric Programming can be implemented on large scale bottom-up models using the paradigm of linear programming. The case study developed in this report concerns the impact of uncertainty on CCS investment cost and electric efficiency. Monte-Carlo analysis consists in generating randomly some uncertain parameters, according to pre-specified probability laws and observing the distribution of model responses. The method fits well with time-stepped computable general economic equilibrium models, like GEMINI-E3. In a final case study one proposes probabilistic scenarios obtained from a combined use of TIAM, with a stochastic programming approach used to determine robust abatement policies, and GEMINI-E3 with an MC analysis to take into account economic and technological uncertainties.

5.2 Insights from the probabilistic scenarios

In the second part of this chapter we summarize the insights gained from these different case studies of probabilistic and robust scenario construction.

5.2.1 Impact of CCS deployment on mid-term climate policies

5.2.1.1 Technology and Policy uncertainty: Implications on CCS and the optimal mitigation portfolio

Uncertainty has important consequences in shaping the decision making process of climate change policies. On the techno-economic side, uncertainty about abatement costs tends to depress the incentive to invest in low carbon technologies. In contrast, climate policy uncertainty might induce earlier hedging abatement. Uncertainty and the related risk of underinvestment in key low carbon technologies is an argument often advocated by policy makers to support command and control measures as opposed to or in conjunction with market-based instruments.

The three issues of policy uncertainty, technology uncertainty, and instrument choice have been addressed using a stochastic version of the WITCH model, in which agents know that, with some probability, different policy and/or technology states of the world will occur, and incorporate such uncertainty in their midterm investment portfolio decisions.

Results indicate that if there is a chance that in the future a high carbon tax will be implemented, it is better to adopt a precautionary behavior and to undertake some abatement in earlier periods. Following an average abatement strategy is sufficient to avoid too high costs in the case of a high tax and it does not require too many investments that would be useless in the case of a low tax. Policy uncertainty also affects the optimal portfolio of abatement options, which includes coal-based power equipped with carbon capture and sequestration (CCS), nuclear power plants, and electricity generation based on renewables. Hedging has a ladder approach in which more flexible options such as coal with CCS are adopted immediately, whereas more costly and less reversible investments, such as nuclear and renewables, are postponed right before the disclosure of uncertainty. CCS is a transitory technology that helps the switch from current, fossil-fuel-based technologies to renewables. CCS is also defined as a bridging technology, exactly because it can fit into the current energy infrastructure without major changes. This result is robust to different spreads between the maximum and minimum possible tax, although for very large spreads, CCS investments are anticipated even more and other mitigation options are used more as a later hedging response. Nuclear and renewables become the main hedging strategies if an even small rate of after-storage leakage of CO2 (0.2% /yr) is considered.

On the other hand, uncertainty about carbon abatement costs decreases investments in low carbon technologies. It mostly affects CCS, because this is the main mitigation option in the mid-term. An equal probability of a 30% increase in CCS costs (compared to the medium, expected value), depresses the incentive to invest in this mitigation option. The same result holds if also the other two mitigation options (nuclear and renewables) are affected by the same risk of low/high costs.

However, when the two uncertainties are combined together, the hedging behavior in CCS investments induced by policy uncertainty prevails. This also explains the last result described in Chapter on complementary regulations. It shows that uncertainty can justify the implementation of emission performance standards (EPS) because they support coal with CCS, which is a hedging strategy. Combining a medium, deterministic tax with an EPS leads to the same capacity that would be optimally achieved if perfect foresight agents could anticipate policy and technology uncertainty. Therefore, regulation could be seen as an option to compensate for the inability of anticipating policy and technology uncertainty.

5.2.1.2 Cost and date of availability of CCS

One has implemented a Monte-Carlo approach on GEMINI-E3 model to analyze the impact of the uncertainty on the cost and on the date of availability of CCS. One observed that the availability of carbon free technologies is determinant for the success of climate policies and that there is no single silver-bullet to combat carbon emissions. Thus, according to the model, CCS alone cannot provide the solution to the problem of GHG emissions increase and we must promote the development of a basket of carbon free technologies. From this perspective, one must encourage the development of substitution among energy forms but also between energy and other inputs. This means also that one must encourage all substitutions, and that the transition to a carbon free economy asked to modify our production process but also our way of life itself.

5.2.1.3 CCS storage potential and climate ambition

The stochastic version of the energy system model TIAMEC was used to study the impacts uncertainty concerning CCS storage potential and climate ambition may have on the mid term energy transition strategies. In addition to the stochastic scenarios, a set of scenarios with perfect information was also run, in order to distill the changes caused by the uncertain limitations for the latter half of the century. The results show that if it is a possibility that a very stringent target may need to be reached, the hedging against the other possible future states is reduced, because the possibility of a stringent target dominates the solution. This is due to the target being fairly close to what is feasible for the model to reach under the given assumptions, leaving very little room for the model to balance the economics across the possible future world states. If the most stringent target envisioned is relaxed, a more balanced hedging solution is suggested by the model. Also, uncertainty concerning the climate target has a much larger impact on the results than the uncertain storage capacity has, implying that on a global level, storage capacity will not limit the use of CCS drastically, or at least the lack of such capacity does not increase mitigation costs considerably.

Despite the above, CCS remains an important option for mitigation and in the mid term (before 2050) its use is the higher the more stringent the target is, or is expected to be. However, during the latter half of the century the most stringent target does not lead to the highest use of CCS, most likely due to the fraction of the emissions that still remain after capture. CCS therefore shows itself as a good option for reductions before the next generation of carbon free technologies becomes available (solar, especially) as well as an important contributor to mitigation also in the long term, even if its use may be limited in case of very ambitious targets.

Costs of mitigation reflect especially the expected climate targets, although clear differences in emission prices can also be observed between cases with similar climate targets, but alternative carbon storage limitations. For example, changing the target from 4.0 W/m^2 to 3.6 W/m^2 increases the emission price in 2040 some 150%. However, the impact of the storage potential is also significant; a further reduction in the assumed storage potential further increases the emission prices of the 3.6 W/m^2 scenario by some 40%.

The scenarios in which a very stringent target is at least possible, lead to very high emission prices, indicating that adaptation measures might have a considerably high economic efficiency and they might take pressure off from the mitigation efforts, which clearly are close to the maximum level considered feasible by the model. Finally, the stochastic scenario that considers the 3.2 W/m^2 target possible, experiences a drastic crash in the price levels, if this target does not come into force in 2050, making a considerable number of prior mitigation investments inefficient. This further emphasizes the importance of adaptive capacity that may be able to soften the harshness of climate regime, as it is seen from the side of mitigation.

5.2.1.4 Perspectives of CCS in Europe

The perspectives of CCS power plants in Europe have been analysed with the Pan-European TIMES model (TIMES PanEU) using the Parametric Programming approach. Thereby uncertainties regarding efficiency losses and additional invest costs compared to the reference power plant without CCS were taken into account. Therefore the routine of Parametric Programming has been applied to TIMES PanEU. The determination of the range of uncertainties associated with these parameters is based on a literature study, which indicates a relevant parameter range of 6-11% points of efficiency loss and invest cost penalties of CCS technologies of 10-40 \$/tCO2 compared to the reference technology without CCS. To reflect ambiguous climate policy regimes in Europe two different GHG reduction paths were analysed, which represent different possible outcomes of international climate protection agreements and can be interpreted as different allocations of greenhouse gas emission permits.

The results show a high influence of climate policy on the market share of CCS power plants. Under an ambitious climate policy regime (-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), driven by the change of the end use sectors towards electric applications. This increase is accompanied by a strong emission reduction in the public heat and electricity sector, which contributes disproportionally high to the achievement of the overall GHG reduction target. Thereby CCS technologies play an important role, achieving a maximum market share in the EU-27+3 in 2050 of almost 40% (2500 TWh) of total electricity generation under a -83% climate target. However under less tight climate targets (here -74% in 2050 compared to Kyoto base) the market share amounts to a maximum of 30% (1700 TWh) in 2050.

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 quantities from CCS power plants up to 600 TWh. Thereby two effects occur. On the one hand, improvements of capture performance can add electricity quantities to the system (up to 500 TWh), satisfying the growing demand and on the other hand, improvements effect the substitution of alternative electricity generation technologies (up to 400 TWh). Under less ambitious climate targets CCS power plants primary substitute non CCS lignite technologies, when entering the market in 2020. Natural gas technologies without CCS are primary substituted in 2030 and 2040 and renewable technologies in 2040 and to a smaller part in 2050. In the long term under tight climate targets less substitution effects occur, since a maximum amount of electricity is demanded, thus improvements of capture performance primary contributes to additional electricity quantities.

Concerning uncertainties and the impact of achievable efficiencies and invest costs of CCS power plants it can be concluded, 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 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.

5.2.2 CCS in perspective of the very long term

One has analyzed the uncertain climatic consequences of leakage over many centuries on CCS deployment using a stochastic version of the top-down integrated assessment model DEMETER. The first main result is that carbon dioxide leakage does not reduce the effectiveness of CCS very much when one assumes a descriptive (high) value for the discount rate and moderate long-term climate change damages. With a 3%/yr pure rate of time preference, even a 1%/yr leakage rate proves to be acceptable in the presented modelling framework. With a prescriptive (low) value for the discount rate, however, leakage becomes problematic: a 1%/yr leakage reduces the attractiveness of CCS very substantially. In order to correctly draw this conclusion, it is imperative that calculations account for the very long-term, that is, as far in the future as the coming millennium. Previous studies have so far failed to do so, including some of our own simulations. Another major outcome of the analysis is that uncertainty regarding the value of the leakage rate and the extent of climate-induced damages to the global economy should not prevent us from using CCS on a large scale. But the deployment of CCS technology should not be fully exempt from carbon taxes. Or, in the alternative policy scenario, emission permits should be bought in order to run fossil-based power plants equipped with imperfect (leakage-degraded) CCS.

5.2.3 Impact of Climate sensitivity

Stochastic Programming technique has been applied to a large scale instances of the Integrated Assessment Model (TIAM). The instances solved and discussed lead to the long term analysis of climate stabilization strategies under high uncertainty of climate sensitivity Cs (in the range 1.5 to 8 C) and of economic growth (simple-to-double GDP growth rates from 2040). Both uncertainties are assumed to be resolved in 2040.

Amongst the most noticeable results, the model reveals that the smallest achievable temperature increase is close to 1.9 C, albeit at a very large cost, by a combination of energy switching, capture and storage of CO2, CO2 sequestration by forests and non-CO2 emission reduction options. This means that more severe temperature targets would require additional GHG abatement potential that is currently not yet seen as realistic. Moreover, the impact of uncertainty of the climate sensitivity parameter Cs is major, requiring the implementation of early actions (before 2040) in order to reach the temperature target. In other words, the "wait and see" approach is not recommended. Robust abatement options include: substitution of coal power plants by hydroelectricity, sequestration by forests, CH4 and N20 reduction. Nuclear power plants, electricity production with CCS, and end-use fuel substitution do not belong to early actions. Among them, several options appear also to be super-hedging actions i.e. they penetrate more in the hedging strategy than in any of the perfect forecast strategies (e.g. hydroelectricity, CH4 reduction), proving that stochastic analyze of future climate strategies might give insights that are beyond any combination of the deterministic strategies. In contrast, the uncertainty of the GDP growth rates has very little impact on pre-2040 decisions. This insensitivity is a pleasant surprise, as it shows that the hedging strategy for only one random parameter is also a quasi-optimal strategy when the two types of uncertainty are present.

The comparison of hedging with perfect forecast strategies shows that a deterministic strategy with Cs=5C is closest to the hedging strategy. However, the two differ in several key aspects, and this confirms the relevance of using stochastic programming in order to analyze preferred climate policies in an uncertain world where the correct climate response is known only far into the future. In particular, the perfect forecast strategy provides a poor approximation of the optimal electricity production mix, of the price of carbon, and of the penetration of several sequestration options.

Among the more sensitive parameters of the problem, resolving the uncertainties in 2020 rather than 2040 induces a 19% reduction in the loss of expected surplus, and keeping the same hedging strategy while assuming a doubling of the exogenous forcing has a non negligible (although moderate) raises global temperature by 0.3 C.

One has also used the computable general equilibrium model GEMINI-E3 with randomly generated uncertain climate sensitivity values to provide a stochastic micro- and macro-economic analysis of a hedging emission policy identified by the Times integrated assessment model TIAM, run in a stochastic programming version (see Chapter. One observed that it is necessary to determine the value of the climate sensitivity parameter as soon as possible. Indeed the model showed that if the climate sensitivity is too high, simply, the climate target cannot be achieved in the CGE model. This impossibility to meet stringent climate target has been also highlighted in the study done by the Energy Modeling Forum [Clarke2009]. It is also showed that the cost of climate policy is very dependent on the climate sensitivity; when the GHG emission constraint is below 7 GtC-eq in 2050, the cost increases very rapidly reflecting the difficulty in reaching the climate target.

5.2.4 Europe energy supply

One has used the approach of Robust Optimization to model uncertainty on the energy supply channels for Europe in the economy-energy model TIAM. The results obtained for the case study exhibit several interesting features regarding the security of EU energy supply. First, it appears that the supply of energy can be guaranteed with a known probability, under the very mild assumption that the means of the random availability factors be known, and bounded at some level higher than half of the range. Second, such reliability is achieved at what may be considered moderate an extra cost, not exceeding 0.7% of the total EU energy cost. Moreover, the results, in addition to ensuring a degree of reliability, contribute very significantly to reduce the concentration of supply sources, a feature that is desirable in itself. The four indexes of concentration used in the study all decrease quite dramatically when the robust solution is used. Finally, the method is easy to formulate and apply and does not increase the computational effort in any significant manner.

5.2.5 Other uncertain factors

The Monte-Carlo simulations performed on the Computable General Equilibrium model GEMINI-E3 have shown that other factors are liable to affect the success and the cost of climate policy. The price of oil and behind it the behaviour of OPEC affects the possibility of reaching a target climate. The climate negotiation must therefore incorporate the specificities of these countries. Note that the oil exporting countries have always conditioned their participation in such an agreement to financial compensation transfers. The economic development of Asia is also a decisive factor in the cost and the success of a climate policy. China and India have to be integrated as soon as possible in the climate agreement.

5.3 General conclusion

This research has demonstrated the use of four different techniques to build probabilistic and robust scenarios concerning the energy system in a climate regime. Although the introduction of uncertainty in the models always yield to a much larger instance of the problem which becomes rapidly numerically intractable, we have managed to produce such scenarios with a variety of multi-region and multi-sector models, using the most recent available optimization and simulation techniques and restricting the analysis to a limited number of uncertain parameters. The different case studies presented in this report have shown, in particular, how one should hedge against the uncertainties on technology deployment and climate sensitivity. Using Monte Carlo analysis with macro-economic and bottom-up modeling we have shown the risks that the climate goals could be unattainable and the necessity to involve all countries in a global agreement on emissions abatement.

Despite the heterogeneity of approaches used, the different scenarios explored in this workpackage convey some common policy insights, which are summarized below.

First, there is not a single silver-bullet technology to combat carbon emissions and CCS alone cannot provide the solution to climate change. Rather, a basket of carbon free technologies should be fostered.

Second, a portfolio response to climate change can help to diversify the risk when there might be leakage of CO2 from the reservoirs. The issue of leakage should also be considered when deciding which sectors should be exempted from carbon taxes or receive free permit allocation.

Third, a portfolio approach to climate change is more effective also because CCS is a bridging technology. It is a good option before the next generation of carbon free technologies become competitive (solar, especially), because it can fit into the current energy infrastructure without major changes.

Fourth, CCS is more sensitive to climate policy uncertainty than to technology uncertainty related to costs, or to storage capacity. The climate policy uncertainty is more pervasive and CCS is competitive only if the climate change cost is internalized through a carbon price.

Finally, regarding the security of EU energy supply, it appears that energy supply reliability can be achieved at what may be considered moderate an extra cost, not exceeding 0.7% of the total EU energy cost. The results, in addition to ensuring a higher degree of reliability, contribute very significantly to reduce the concentration of supply sources, a feature that is desirable in itself.