# Climate Change Scenarios Evaluated with MERGE-ETL and Technology Transfer Protocols

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**Abstract:** We apply a specific version of MERGE-ETL, an integrated assessment model that provides a framework for assessing climate-change management proposals, to study global climate policies supported by Technology Transfer Protocols (TTP). We model a specific formulation of such a TTP where donor countries finance, via carbon-tax revenues, the diffusion of carbon-free technologies in Less Developed Countries (LDCs) and quantify its benefits. Industrialized countries profit from a global diffusion of advanced technology, the induced cost reduction, and the reduction of climate damages through the likelihood of greater global participation in a new international agreement based on TTPs. On the other hand, the cost-free technology transfer to LDCs will increase their welfare, generating a positive feed-back mechanism supporting participation. LDCs will also profit from the reduction of damages related to climate change, while the expected secondary benefits of carbon control related to the improvement of local environments will be significant. An explicit specification of subsidies per technology and time, supporting by mitigation targets, is needed such that the proper price signals are passed to consumers to avoid possible rebound effects of higher energy demand and emissions. The proposal is only likely to be adopted if an increased willingness to pay to avoid climate damages is accepted, first by the present and future generations of the industrialized world and later on, when sufficient economic growth is accumulated, by today's less developed countries.

**Keywords**:

MERGE, Climate Change, Burden sharing, Technology Transfer Protocol

# Introduction

*Why are Technology Transfer Protocols (TTPs) important?*

Securing international agreement on measures to address global climate change has proved to be an elusive goal for the past decade. On the one hand, the challenge of climate change demands a global response, while on the other, there are barriers related to encouraging participation in a way that recognizes responsibility and financial and technological capacity. To overcome some of these challenges, it is clear that new innovative ideas need to emerge in order to realize a successful Post-Kyoto framework. One area where in which there exists potential for novel approaches that may break negotiation deadlocks in the UNFCCC is in the treatment of technology, specifically technology transfer (Bazilian et al., 2008).

Our technological systems, and especially our energy and transportation sub-systems, represent key factors that have driven economic growth since the industrial revolution. However, these systems also represent a key challenge to long-term sustainability and the successful mitigation of climate change, since they are the principal source of anthropogenic greenhouse gas emissions. Accordingly, technology and technological change in energy and transportation systems must play a major role in our response to climate change. To support such technological change and ensure mitigation efforts are effective and politically acceptable globally, the necessary technologies need to be available to all those parties expected to undertake emissions abatement activities, which ultimately means all countries.

Technology Transfer Protocols (TTPs) are agreements for supporting the transfer to developing countries of the low- and zero-carbon technologies needed for an effective global response. In this way, they may also represent an attractive method of garnering support for a new international agreement. The term “technology” in the analysis of TTPs in this study refers to renewable energy, fossil fuels with carbon capture and storage (CCS) and low-carbon systems producing alternative transportation fuels like synthetic fuels, biofuels, gaseous fuels and hydrogen that face technological, institutional or economic barriers and need support to emerge in the marketplace. We regard also advanced generation IV nuclear breeder reactors as part of the TTP since they have zero emissions during operation and face significant barriers to deployment associated with high capital cost, waste disposal and proliferation. TTP should include also energy conservation and innovative end-use technology with improved efficiencies and low carbon emissions during operation, but they are not included in our study.

TTPs are likely to have a range of impacts in developed and less-developed countries. For instance, the cost-free (or low-cost) transfer of technology and know-how to less-developed countries will increase their welfare, generating a positive feedback mechanism encouraging participation. For industrialized countries, the costs of supporting technology transfer (such as through transfer payments to less-developed countries) will reduce economic welfare, but this will be partly offset by additional technology exports (fabricated by their industry or elsewhere under their license). In addition, both developing and developed countries will benefit from the induced technological learning resulting from the higher overall deployment of new technologies, which will reduce the cost of achieving global mitigation targets in a post-Kyoto agreement. Both will benefit also from the reduction of damages related to climate change, and secondary benefits of carbon control related to the improvement of local environments which are also likely to be significant.

The study analyses a specific example of TTPs as an innovative cooperation mechanism where developed countries support the deployment and sharing of carbon-free technologies in developing and emerging economies to meet climate targets towards a sustainable global energy system. Among the keys factor in the design of TTPs is the question of how the mechanism of technology transfer and deployment is funded, and here we analyze various options of supporting transfer with revenue recycled from a carbon tax.

To assess the merits of a post-Kyoto agreement that encompasses TTPs, we applied a new version of MERGE-ETL in which we have introduced a technology transfer mechanism to support carbon-free technology in less-developed countries. Specifically, we have introduced an explicit representation of technology and capital transfer (See also Appendix). The objective is to understand how this may establish a diffusion of carbon free technologies in the market place, reinforce climate change policies and reduce losses in welfare associated with mitigation efforts.

## Methodology

We apply a modified version of MERGE5 (Manne and Richels, 2004a, b), referred to as MERGE-ETL. Key features of MERGE-ETL include: a nine-region global disaggregation; a combined ‘top-down’ Ramsey-type economic and ‘bottom-up’ engineering modeling approach; a simple climate model with a damage function; and international trade in a range of goods and resources. Regional technological learning with global spillovers, climate-change impacts and the associated damages further enhance the regional links and interactions.

Energy technologies representing electricity generation (including options for carbon capture and storage (CCS)), and secondary fuel production (synthetic fuels from coal and biomass; H2 from a range of sources; including some options for CCS) have been explicitly introduced in MERGE-ETL as well as open and closed nuclear fuel cycles and advanced reactors. Technological learning in MERGE-ETL (see Barreto and Kypreos, 2004 and Kypreos, 2005a, b, 2007) is represented by two-factor learning curves for the investment costs of each learning technology (Magné et al. 2009). The paradigm of technology clusters described in Seebregts et al. (2000) is applied, considering that development and adoption of technologies occurs as a collective evolutionary process. The model introduces as control variables R&D spending and “learning investments”, which is seen as large scale demonstration projects in favor of carbon-free technologies, such that technological breakthroughs become scenario and path dependent developments and an endogenous model property.

MERGE relies on assumptions about perfect competition and information, and utility function continuity, representative agents and so on, and thus provides a normative representation of market development. In addition, the level of technology detail enables only a generic representation of end-use energy efficiency (i.e., explicit end-use technologies are not represented with the exception of the private transport systems) and price effects on demand. Further, there is substantial uncertainty concerning many of the parameters used in the model related to resources, economic development, demands and climate change. The representation of climate damage enables the model to be used in a cost/benefit analysis (CBA) mode to evaluate levels of “optimal emission control”, concentrations of GHGs in the atmosphere, climate forcing and temperature change under descriptive or prescriptive utility discount rates and for different levels of willingness to pay (WTP). Technologies included in the model and their cost data are described in Table 1, while the data sources are given in Magné *et al*. (2009).

To model technology transfer and TTPs, a new set of decision variables related to technology transfer have been introduced, along with a modified set of capital transfer and production balance equations. In summary, the subsidized activity $SACT_{R2,t,k}$, defines the amount of electric or non-electric energy in less developed Non-Annex B regions of the Kyoto Protocol to be supported via capital transfer payments $TTRX_{R1->R2,t}$ from donor countries (i.e., the Annex B regions) bounded by the tax-revenue of donor regions. The subsidized part of the cost refers to the learning part of a carbon-free technology in non-Annex B regions e.g., the annualized investment cost of key components of Table 1 (See also Appendix).

| Electric | | | | | BOP | | | | Key components | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lifetime years | Eff | Load factor | Inv. Cost $/kW | O&M $/kW/y | Var O&M U$/GJ | Feedstck $/GJ | Inv. Cost $/kW | O&M $/MWh | Gen-Cost mills/kWh |
| oil-r | Exist. | 20 | 0,303 | 0,65 | 991 | 63,6 | 0,57 | 3 | 0 | | 62,83 |
| gas-r | Exist. | 20 | 0,333 | 0,65 | 987,7 | 50,6 | 0,56 | 2 | 200 | | 49,26 |
| ngcc | NGCC | 20 | 0,51 | 0,65 | 360 | 36,6 | 0,63 | 2 | 200 | | 30,7 |
| ngcc-a | " & CCS | 20 | 0,459 | 0,65 | 360 | 60 | 0,88 | 2 | 742 | 86,4 | 45,91 |
| gas-fc | Gas FCell | 20 | 0,599 | 0,65 | 1213 | 43,5 | 0,63 | 2 | 1250 | | 56,63 |
| coal-r | Existing | 30 | 0,37 | 0,65 | 1050 | 38 | 0,72 | 1,6 | 0 | | 36,83 |
| pc | Pulv. Coal | 30 | 0,429 | 0,65 | 784 | 47,5 | 0,75 | 1,6 | 800 | | 42,56 |
| pc-a | PC& CCS | 30 | 0,365 | 0,65 | 784 | 90 | 1,13 | 1,6 | 1342 | 86,4 | 60,93 |
| igcc | IGCC | 30 | 0,425 | 0,85 | 901 | 40 | 0,88 | 1,6 | 500 | | 34,33 |
| igcc-a | " & CCS | 30 | 0,361 | 0,85 | 901 | 52 | 1,23 | 1,6 | 1009 | 42,3 | 44,42 |
| nuc | Exist. | 30 | 0,327 | 0,8 | 1800 | 70 | 2 | | 0 | | 7,2 |
| nuc-a | Gen IV | 30 | 0,345 | 0,85 | 0 | 70 | 4 | | 2200 | | 14,4 |
| hydro | Existing | 50 | 1 | 0,45 | 2850 | 49,5 | 0,12 | | 0 | | 52,59 |
| bio-a | Bio &CCS | 20 | 0,4 | 0,75 | 1091 | 146 | 0,92 | 2 | 1409 | | 74,06 |
| wnd | Wind-all | 20 | 1 | 0,3 | 0 | 13,5 | 0,83 | | 1200 | | 44,76 |
| spv | Splar PV | 20 | 1 | 0,3 | 0 | 9 | 1,25 | | 5000 | 4,2 | 160,68 |

| Non Electric | | | | | BOP | | | | Key components | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Resource ZJ | Life years | Eff | Load factor | Inv. Cost $/kW | O&M $/kW/y | Var O&M U$/GJ | Feedstck $/GJ | Inv. Cost $/kW | O&M $/MWh | Cost U$/GJ |
| oil1-10 | 12-18. | ND | 1 | | | | | | ND | | *3-5.25* |
| gas1-10 | 20 | ND | 1 | | | | | | ND | | *2-4.25* |
| coal1-10 | 100 | ND | 1 | | | | | | ND | | *2* |
| ura | | ND | 1 | | | | | | ND | | |
| bio | 250 | ND | 1 | .65 | | | | | ND | | *2-10.* |
| coal-FT | | 30 | 0,65 | 0,8 | 550 | 80 | 1 | 1,6 | 500 | | *9,34* |
| bio-FT | | 30 | 0,51 | 0,8 | 1150 | 80 | 1 | 2 | 1409 | 42,3 | *14,8* |
| gas-H2 | | 40 | 0,7 | 0,9 | 600 | 60 | 3 | 2 | 0 | | *9,2* |
| gas-a-H2 | | 40 | 0,7 | 0,9 | 600 | 60 | 3 | 2 | 200 | | *9,61* |
| coal-H2 | | 30 | 0,65 | 0,8 | 700 | 60 | 3 | 1,6 | 300 | | *10,42* |
| coal-a-H2 | | 30 | 0,6 | 0,8 | 700 | 60 | 3 | 1,6 | 500 | | *10,93* |
| bio-H2 | | 30 | 0,5 | 0,8 | 350 | 60 | 3 | 2 | 1100 | | *13,12* |
| nuc-H2 | | 30 | 0,5 | 0,8 | 0 | 0 | 3 | | 3400 | | *11,77* |
| sth-H2 | | 20 | 0,3 | 0,35 | 0 | 0 | 3 | | 4500 | 2,8 | *35,73* |

Table 1: Technologies included in MERGE-ETL and their cost structure. Investments costs are split into the Balance of Plant (BOP) and the Key component cost subject to learning. Feedstock prices are indicative as the time development of prices is endogenous to the model and depends on the use of reserves and resources while the generating cost refers to the initial investment cost specifications for the key components. The subsidy fully covers the investment cost of the key components for the low-carbon technologies in this form of TTP.

## The Baseline

We first describe the baseline development which is based on the assumptions made in the EU ADAM project (http://adamproject.info/), fine-tuned with the baseline scenario development generated by the TIMER model (van Vuuren, et al. (2006)) for that project. This baseline excludes technology transfer support mechanisms.

In the Baseline, electricity production increases, as consequence of population and economic growth and a moderate improvement in energy intensity, from 15 PWh in 2000 up to 98 PWh by 2060 while the primary energy use increases from 400 EJ to around 1000 EJ by 2060. Existing fossil fuel-based thermal plants are progressively phased out and are replaced firstly by a combination of NGCC and IGCC plants, and then by IGCC, owing to its relatively high efficiency and low fuel cost. Next to IGCC, wind turbines followed by nuclear reactors are the most competitive power generation systems. The cost of wind power improves substantially thanks to learning-by-doing. Wind power complements the power supply up to its maximum potential, assumed to be 25% of overall electricity generation by region. Finally, primary energy is mainly provided by coal followed by renewable energy forms, gas and oil. As a consequence, carbon emissions reach a level of 16 GtC/year by 2060. Some cost benefit cases (CBA) have been examined with the time horizon up to 2100 but are not presented here as with one exception needed to compare the TTP scenarios discussed later on with “first best” scenarios on climate change.

Next we select two different emission reduction targets, the first consistent with an atmospheric concentration target of 550 parts per million volume (ppmv) carbon dioxide equivalent ($CO_2$e) and another of 450 ppm $CO_2$e, to establish temperature changes that significantly reduce carbon damages, e.g., below the 2°C target of the European Parliament (European Commission 2007).

## Stabilize Carbon Concentrations (SCC) or Cap & Trade (C&T) cases

Here, we evaluate scenarios that stabilize greenhouse gas (GHG) concentrations at 450-550 ppm $CO_2$-equivalent with an unrestricted participation of all world regions, e.g., we define efficient solutions of GHG control on the global level. We discuss the needed technological change together with the economic losses. All scenarios are estimated with a descriptive utility discount rate of 3 percent. The scenarios are called:

**SCC550: Stabilize GHG concentration to 550e**

**SCC450: Stabilize GHG concentration to 450e**

Next we simulate global cap and trade (C&T) scenarios that stabilize GHG concentrations following the global emission reduction targets estimated in these SCC scenarios, applying an allocation of emission permits that starts with a grandfathering rule and ends with equal emission rights per capita after 2050. This scenario represents a possible future burden-sharing arrangement, which we later compare with possible technology transfer protocol scenarios. For these C&T cases we compare economic losses by region and the needed technological breakthroughs. Capital transfers due to the permit trade are accounted for in the estimation of net economic losses/gains by region. The cases are abbreviated as:

**550C&T: Cap global carbon emissions at SCC550 level with trade of certificates**

**450C&T: Cap global carbon emissions at SCC450 level with trade of certificates**

The subsequent figures 1, 2 and 3 illustrate the electricity production, the primary energy and the carbon values respectively.

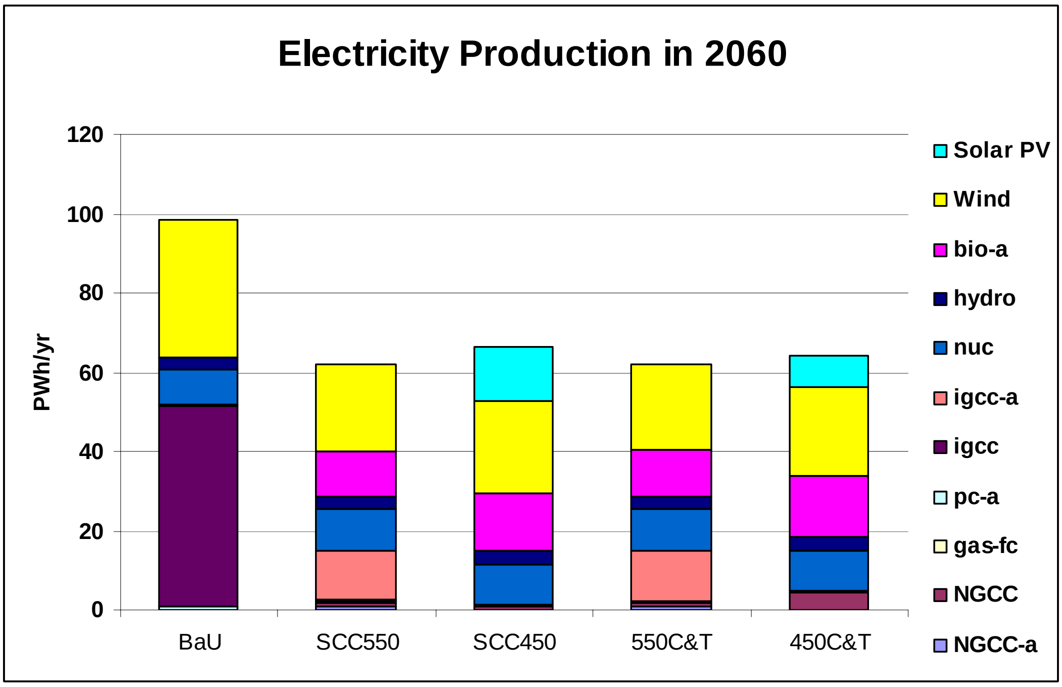


Figure 1: Electricity production in the year 2060 for the Baseline, the SCC and the C&T cases.

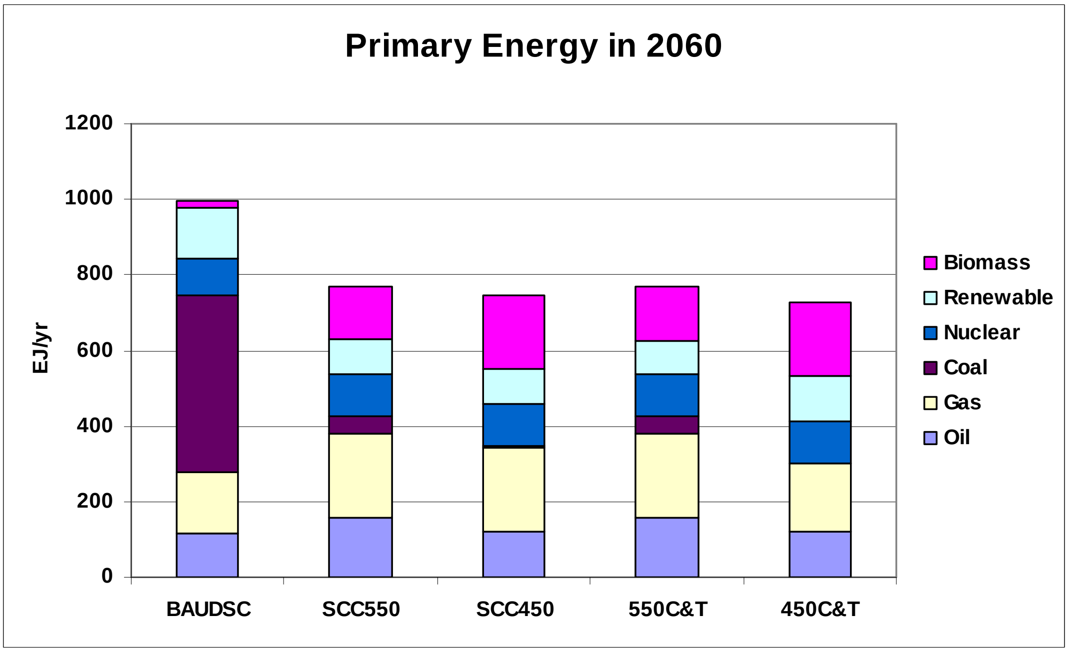


Figure 2: Primary energy production in the year 2060 for the SCC cases. The cost of carbon control reduces energy demand.

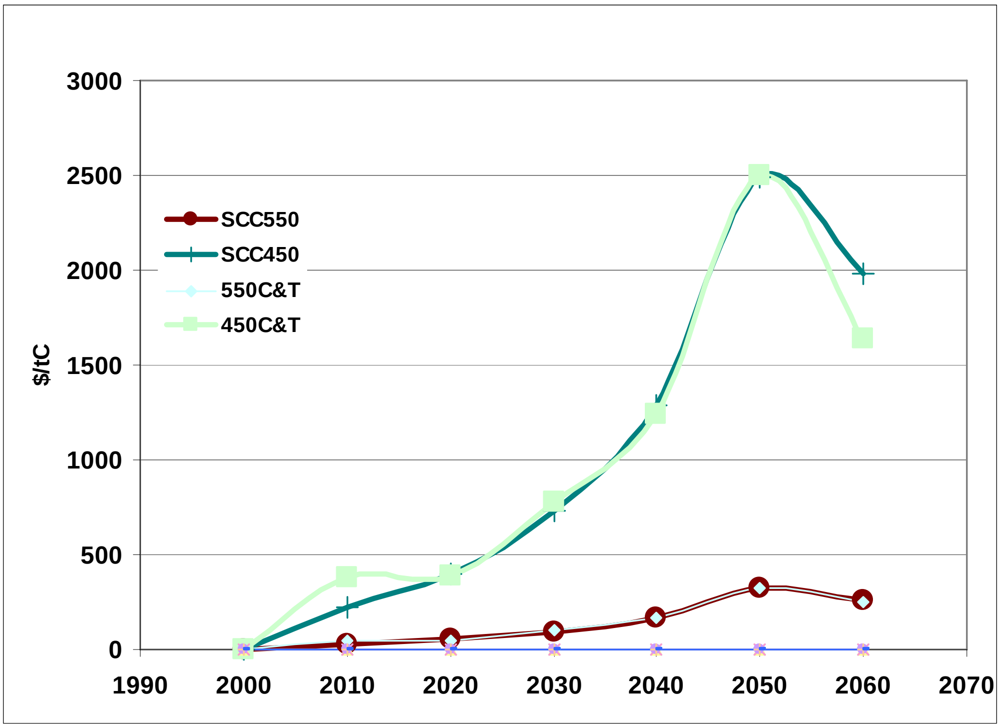


Figure 3: Marginal costs for the stabilization cases.

Clearly, the SCC and the C&T cases needed to restrict the increase in average global temperature to below 2°C induce high marginal control cost such that reaching a global agreement for common actions is likely to be challenging. On the other hand, prices in the 550 ppm cases by the end of time horizon remain well below 500 $/tC.

The carbon constraint generally shifts production to carbon-free technology, increases the production cost of electricity and reduces the energy demand. This behavior increases as more stringent policies are imposed. Wind turbines become the largest source of power generation in all carbon control cases versus coal IGCC in the baseline. We notice also that the key difference in power generation in the two stabilization cases is the use of IGCC with CCS in the 550 ppm case versus zero-emission options in the 450 ppm case. Also, solar PV systems become competitive under stringent emission control scenarios.

The economic losses (Fig. 4) associated with these scenarios continue to be high even with some capital transfers from industrial to LCD countries for emission permits.

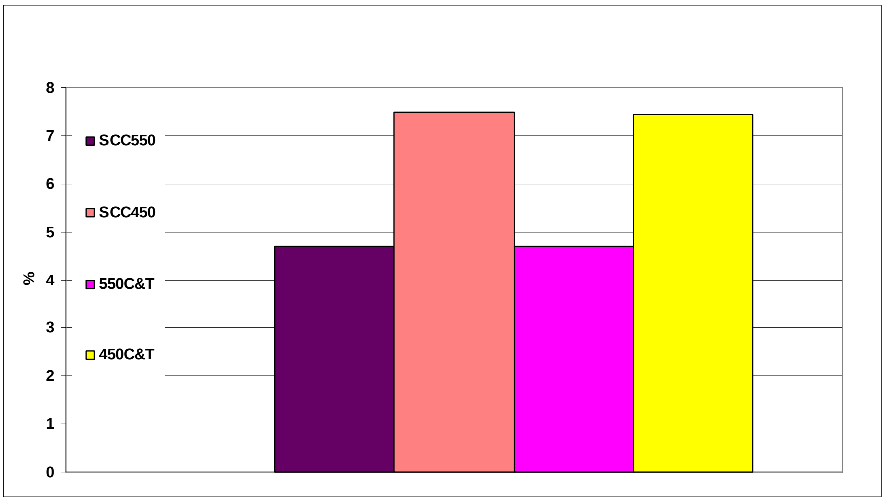


Figure 4: Cumulative and Undiscounted global GDP losses relative to Baseline in percent (over the period 2000-2060). Clearly the losses in the Stabilization cases are high while there is no difference in the estimates (as expected) when a C&T policy is applied instead of a CCS target. Notice that discounted losses are much lower than the undiscounted values shown above as most of actions take place at the later decades.

## Tax and Subsidies in the form of a TTP

Finally, we adopt a New Protocol that combines emissions taxes with supporting policies for carbon-free technologies via global R&D spending, learning investments and technology transfer to LDCs, to be financed with the revenues from the GHG taxes (see also Young and Nordhaus (2006)). We refer to this as a Technology Transfer Protocol (TTP). We consider three different mechanisms of the proposed strategy which vary according to the regional coverage and timing of the emissions tax. In all cases, all the revenue from the tax is directed towards less-developed regions (i.e., non-Annex B countries), as a means to encourage their participation. The three mechanisms are as follows:

a) Taxes are applied globally but the tax revenue of the industrialized world is used to support technology transfer to LDCs. The tax-revenue in the developing world supports their own technology in form of subsidies. The scenario names are abbreviated first with a GT (Global Tax), followed by S for subsidies and then the concentration level:

- **GTS550: Global taxes as in SCC550e and recycle total revenue to non-Annex B**
- **GTS450: Global taxes as in SCC450e and recycle total revenue to non-Annex B**

b) Taxes are introduced only in the industrialized countries, again with the revenues used to support technology transfer to LDCs. The scenario names are abbreviated first with a BT (Annex B-Tax), followed by S for subsidies and the concentration level:

- **BTS550: Taxes as in SCC550e in Annex B and recycle revenues to non-Annex B**

- **BTS450: Taxes as in SCC450e in Annex B and recycle revenues to non-Annex B**

c) Taxes are introduced first in the industrialized countries and with a delay of 30 years in the LDCs (e.g., the tax level in 2040 for LDCs is the same in 2010 in the respective GTS case), while all revenues are either transferred to or remain in the LDCs to support carbon-free technology. The scenario names are abbreviated first with a GRS (Global Reduced-Tax + Subsidy), followed by the concentration level:

- **GRS550: Taxes as in SCC550e in Annex B with 30 year delay of taxes in LDCs, but recycle total revenue to non-Annex B**
- **GRS450: Taxes as in SCCS450e in Annex B with 30 year delay of taxes in LDCs, but recycle total revenue to non-Annex B countries:**

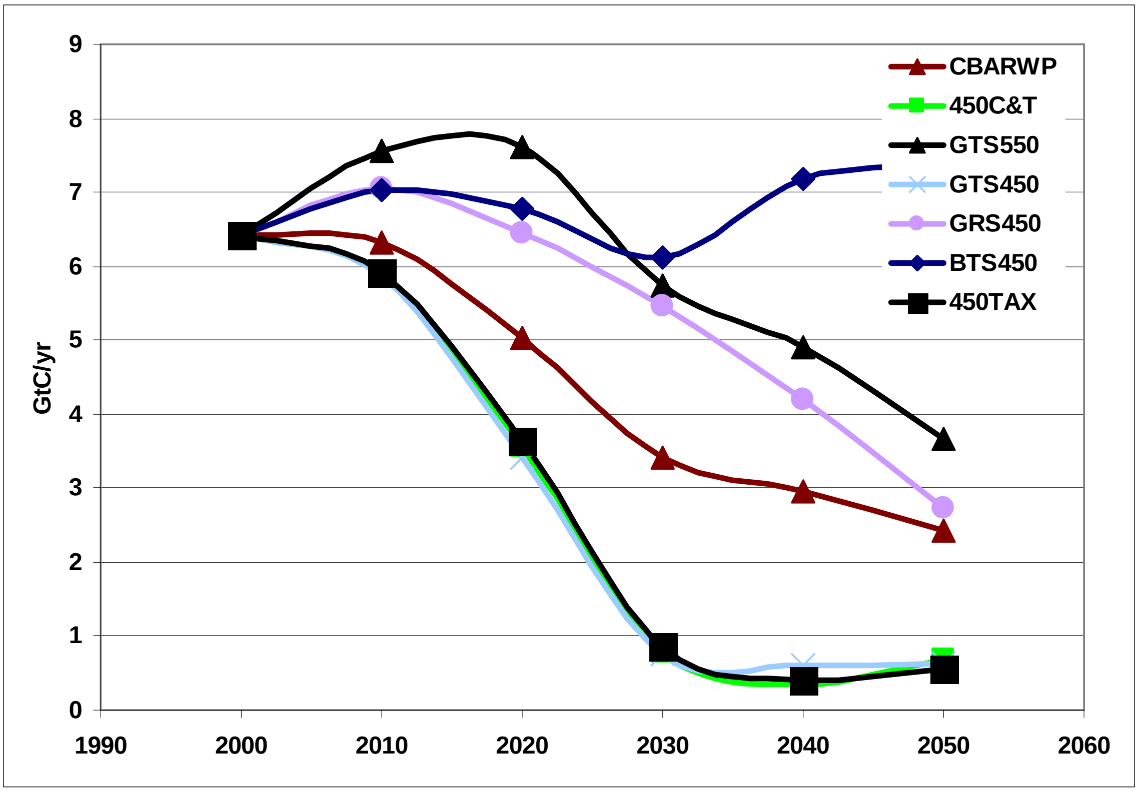
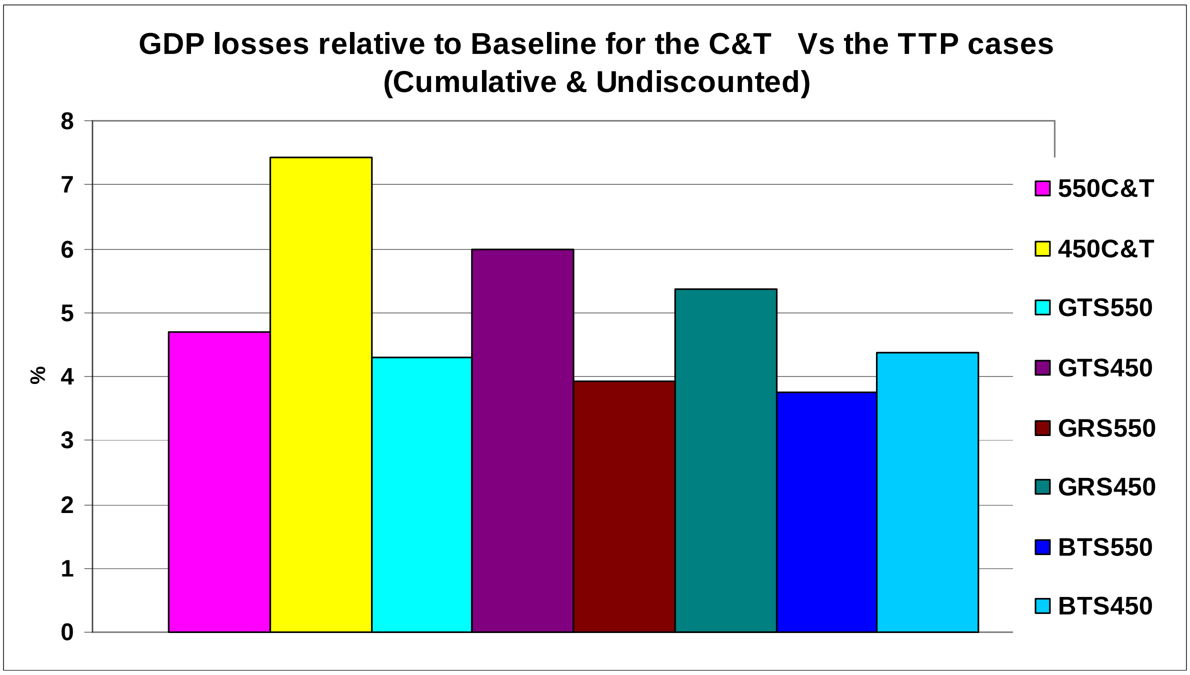


Figure 5: Global emission pathways for the tax-subsidy cases Versus the C&T cases. Here we include also the results of a Cost/Benefit case estimated with an almost zero utility discount rate (CBARWP) and the reference damage cost function of MERGE that results in emissions of 2.5 GtC/yr in 2060, e.g., almost the same level of emissions in 2060 as in the GRS450 case.

Figures 5 presents the main results concerning the emission reduction obtained while Figures 6 and 7 refer to the welfare implications for the cases where the TTP applies. In the case of BTS450, where taxes are imposed only in Annex B countries to subsidize carbon-free technology in LDCs, global emissions continue increasing after 2030 because LDCs face no incentive to reduce emissions, and coal continues to play a dominant role in primary energy use. The other extreme case is the GTS450 where a global tax is imposed to all world regions. Here, the subsidies do not result in additional abatement because the stringent tax alone provides a strong incentive to adopt carbon free technologies throughout the world. However, Figure 6 shows that the TTPs allow this target to be met at lower cost to global GDP; and in this way is likely to provide a mechanism to increase global support and participation (to which we return below). Finally, the GRS450 case presents what could be considered a compromise scenario where LDCs accept a tax after 30 years, e.g., when sufficient economic growth is accumulated[1] and is much better than the case with a global tax at 550 ppm. However, such a scenario is not sufficient to meet ambitious abatement goals such as the EU target of restricting the temperature increase below 2°C by the end of the century, for which concentrations around 450 ppm $CO_2$e are likely required (Meinshousen, 2006) following an emission path similar to GTS450. These results together show that technology transfer supporting low-emissions technologies is not sufficient to promote stringent abatement in LDCs, and must be combined with strong policy targets. However, the results support the notion that technology transfer can reduce the costs of achieving such strong targets, and thus make these targets more acceptable. This is highlighted in Figure 7, which shows how the technology transfer to LDCs can substantially reduce the costs of joining an international abatement regime early (and provide net benefits in some cases). Figure 7 shows for China and India that with more stringent policy targets, TTPs can approximately halve the GDP costs from participation—noting that this is compared to a scenario which includes a transition to an equal per capita burden sharing arrangement.[2] Similar trends are valid for the other TTP cases studied.



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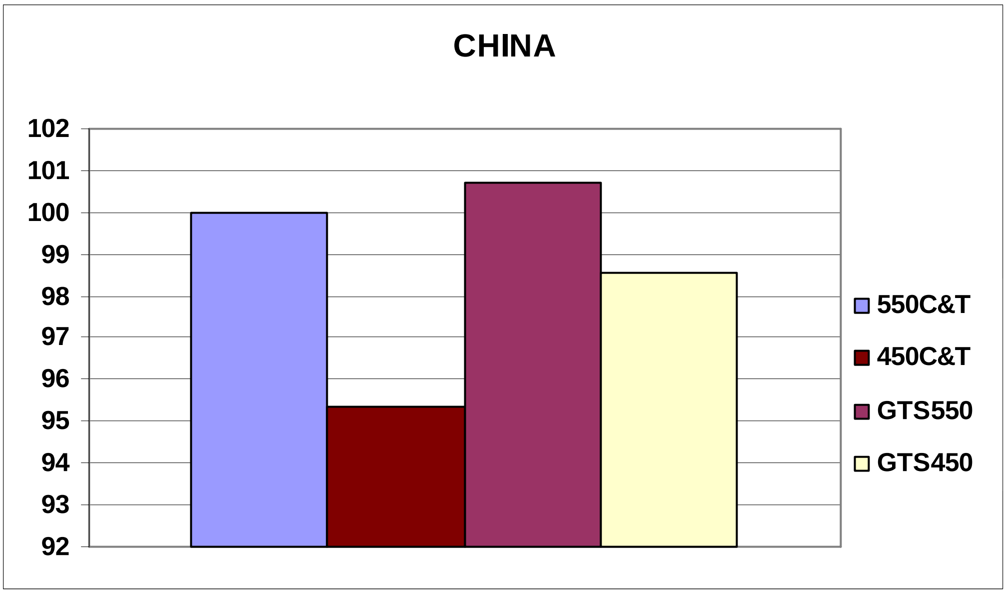
[1] We have tried to compare the TTP results with Cost/Benefits cases where we take into consideration the induced damages of climate change as formulated in MERGE. The GRS450 case is similar to the CBA case estimated with the reference damages of MERGE and an almost zero discount rate (CBARWP),

[2] With similar results for a simple carbon tax scenario.

Figure 6: Global GDP changes relative to Baseline for the C&T and TTP cases. TTP reduce global losses significantly in the case of stringent policies. In the cases of a global tax where the results are comparable; the global GDP gains are trivial in the case of 550C&T versus GTS550 but losses are reduced from 7.4% in the C&T case to 6% in the cases of GTS450. Similar gain ranges are expected when the revenue of Annex B is recycled in favor of non-Annex B regions or when the carbon tax is shifted by 30 years for the non-Annex B countries.



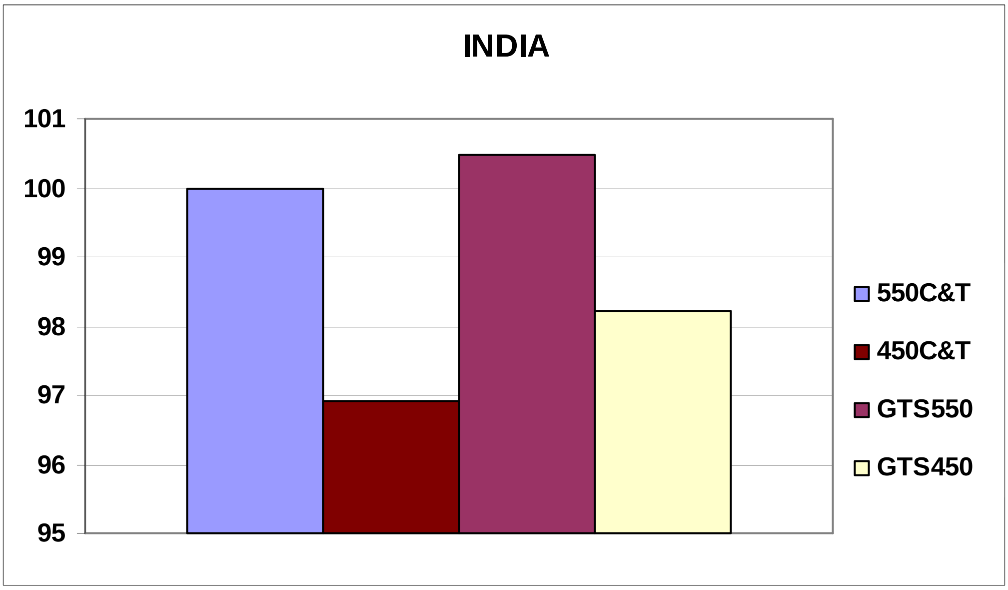


Figure 7: Regional cumulative and undiscounted GDP changes for China and India for the TTP cases relative to the C&T cases. Although in the case of C&T increasing the stringency of carbon control reduces GDP by 4.8% (e.g., for China) and 3.1 % (e.g., for India) in the case of TTP we have a net benefit of 0.8% for China and 0.6% for India for the GTS550 case, in the case of GTS450 the gains are 3.3% for China (above the corresponding 450C&T case)

and 1.3% for India as subsidies also increase in magnitude and in effectiveness when supporting carbon free technology.

### *The impact of the subsidy on the energy system*

As seen above, TTPs reduce the global economic cost of achieving the 450 ppmv $CO_2$e target, particularly in less-developed countries. One of the mechanisms by which this occurs is through the impact of the TTP subsidy to reduce energy costs, resulting in higher energy demand (and economic growth). To illustrate the effect on the energy system, Figure 8 shows how the primary energy demand develops for the different scenarios. The first thing to notice is that energy demand is highest in those scenarios in which fewer countries face carbon constraints (e.g., BTS) or LDCs are subject to less stringent constraints, (e.g. GRS). However, even in the GTS cases with full global participation, energy demand is significantly higher than in the C&T cases, despite emissions being almost identical (see Figure 5). The increase in energy demand is particularly strong in the case of 550 ppm where the tax revenue (and subsidy) is high. It should be noted that in the BaU case the primary energy use is 1000 EJ, and all 550 mmpv $CO_2$e cases with the subsidy exceed this level, while in the C&T cases primary energy remains below 800 EJ. We have similar behavior in the electricity markets (Figure 9), where we see the TTP subsidy has a particularly strong impact on advanced nuclear generation.[3]

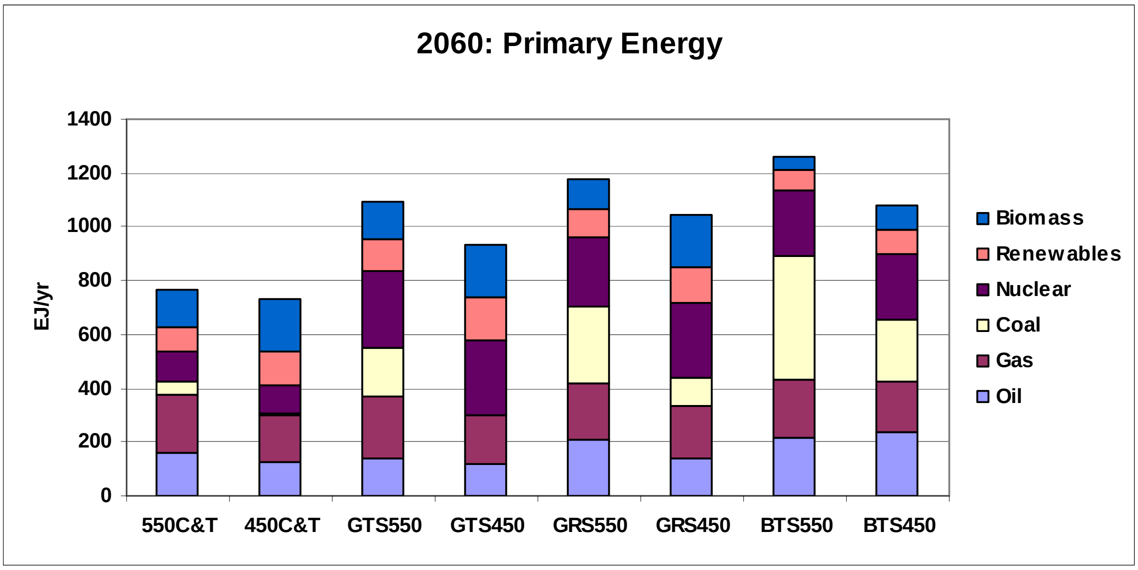


Figure 8: Primary energy supply C&T Versus Tax-Subsidy cases. The reduced cost of energy in the LDCs as results of the subsidies reduces the price of energy and increases the demand.

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[3] The fact that this technology is deployed under these scenarios further contributes to the high levels of primary energy demand. For nuclear generation, we assume a thermal efficiency of approximately 35 percent.

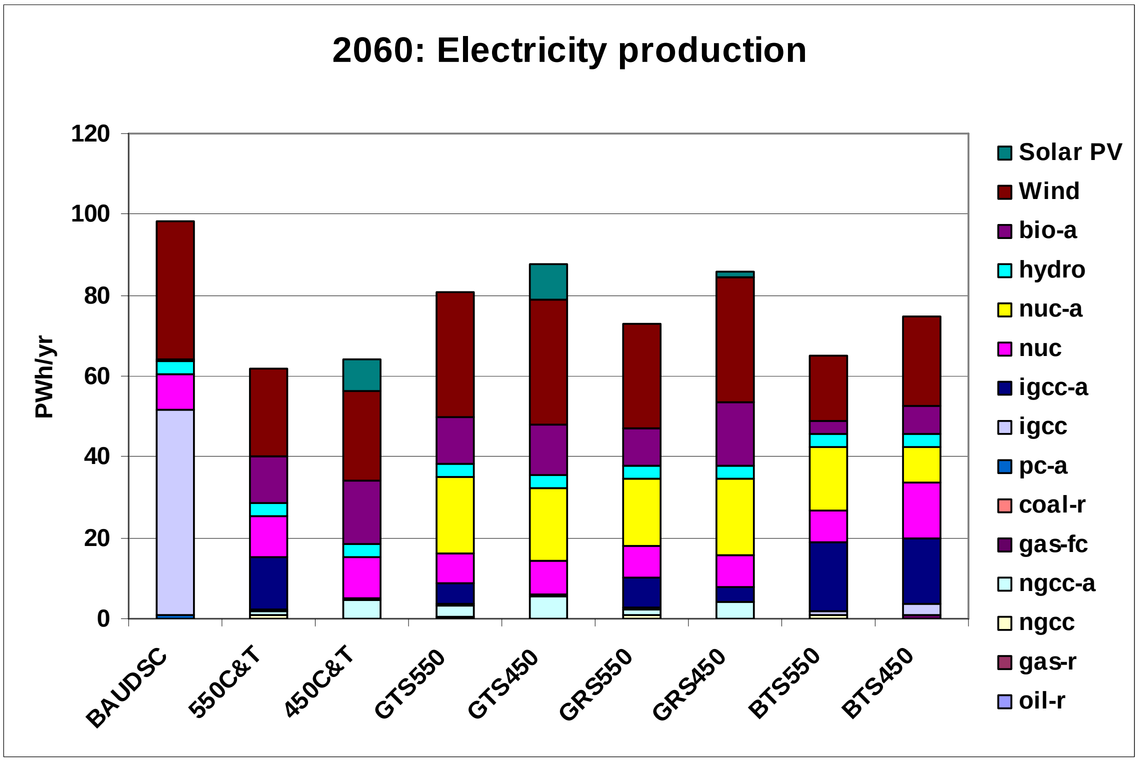

Figure 9: Electricity production for selected cases.

These results go some way towards showing why the TTP by itself is unlikely to support sufficient abatement activity in LDCs, without accompanying abatement commitments. Specifically, although a TTP supporting renewables and other advanced low-emissions technologies may reduce the relative competitiveness of fossil technologies, the impact on overall economic activity and energy demand may still result in higher emissions than would otherwise be the case. Accordingly, the TTP is unlikely to substitute for global commitments on abatement.

Next Figure 10 explains how the tax revenue of Annex B countries is absorbed by the Non-Annex B regions supporting carbon free technologies. A ratio equal to one means that 100% of the tax revenue is absorbed while when the index is above one the origin of extra support is the regional tax revenue in LDCs. As we can see, later in the time period LDCs become the main source of financing for the technology support. Interesting is that in the first two decades the support is below 25% and 75% of the collected tax revenue in Annex B countries. This is a result of the optimization that takes into account the inertia of the energy system expressed as capacity expansion constraints. Importantly, the present formulation does not allow for the banking of tax revenues for technology support, so some of the tax revenue in the initial periods is wasted. If we did allow for banking, more support for technology transfer would be available and the results seen above would have been amplified.

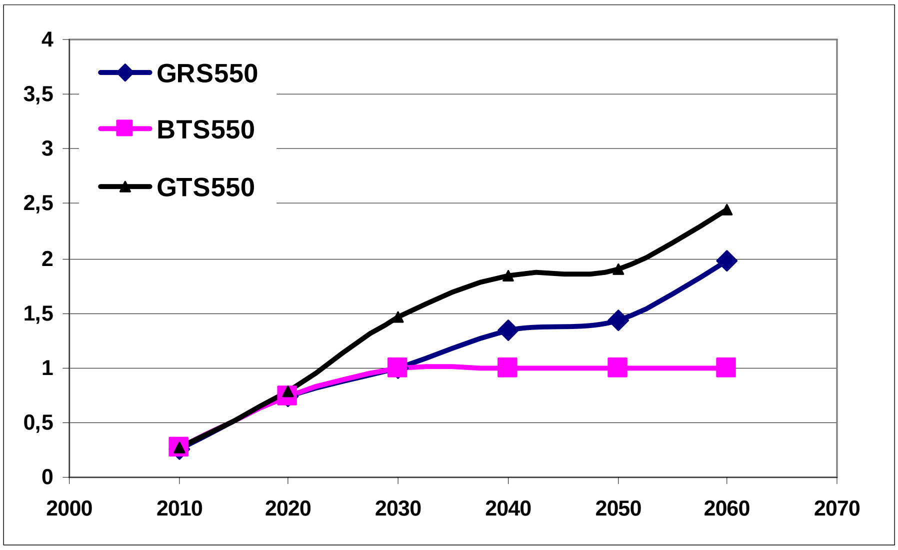

Figure 10: The ratio of Learning Subsidies in LDCs to the Carbon Tax Revenue of Annex B countries.

The annual amount of learning subsidies for the 550 ppm $CO_2$e cases is shown in Figure 11 given in million US Dollars with the purchasing power of the year 2000. A significant share of the subsidies for carbon-free technology originates in the Annex B countries and corresponds to their tax revenue, while another part corresponds to the own tax revenue of LDC counties and becomes dominant at the end of time horizon.

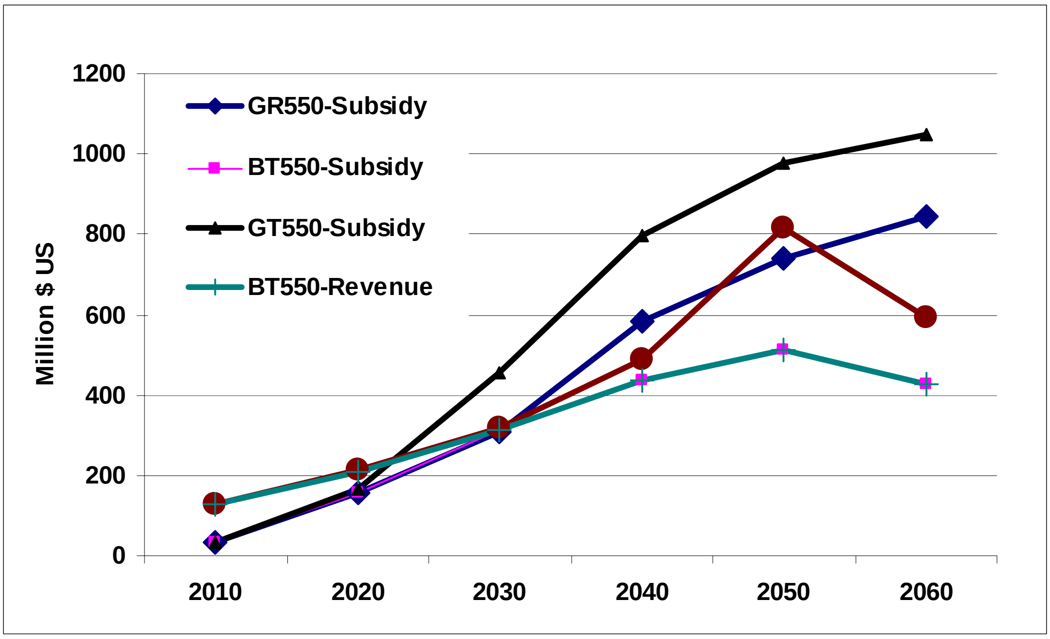

Figure 11: Annual global subsidies Versus Tax-Revenue in Annex B countries. The difference between the "Subsidy" and the "Revenue" of Annex B countries is due to the tax revenue of LDCs invested in carbon free technology.

Another interesting observation is that only power generation technologies are supported in the 550 ppm cases distributed as shown in Fig. 12 while the spectrum of supported technologies is extended in the case of more stringent emission control policies.

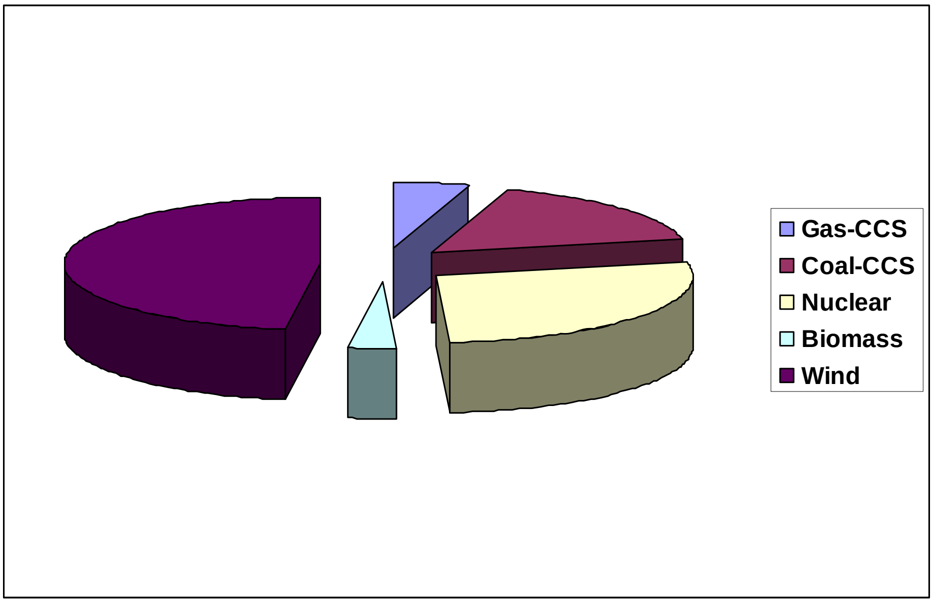

Figure 12: Cumulative Learning Subsidies (2010-2070) by Technology for the GRS550 case in Non-Annex B countries. Most of the support is in favor of wind followed by CCS options and nuclear energy.

Finally, Figure 13 compares the cumulative production of selected technologies in both 450 ppm $CO_2$e cases (e.g., the C&T case and the global tax-subsidy case) aiming to identify the impact of TTP in inducing technological change. Examining the graph we conclude that the learning subsidy is making the difference for some technologies like New Nuclear (NNU) and solar PV (SPV) while in some other technologies, already competitive without subsidy, the contribution is marginal. This fact also calls for more elaborated ways in defining the level of subsidy per technology such that the needed price difference for a technology to become competitive should be taken into consideration.

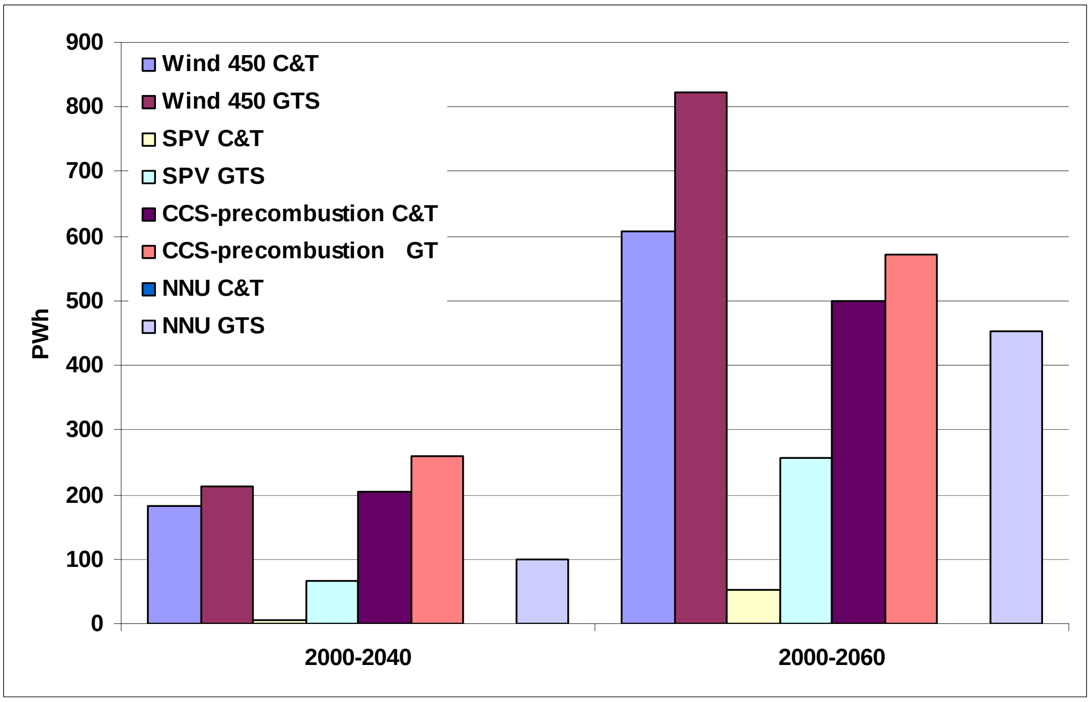

Figure 13: Cumulative production of electricity for the period 2000-2040 and 2000-2060 for selected technologies and for the 450 C&T Versus the 450GTS case.

## Conclusions

The simulation of development, deployment and transfer of low-carbon technologies, and the related investment challenges, is of primary importance to properly analyze the potential benefits of Technology Transfer Protocols. This work should be seen as the beginning of more detailed analysis needed to assess properly the benefits of TTPs based on Integrated Assessment Modeling with sufficient technological representation.

MERGE-ETL incorporates LbD and LbS as a mechanism that allows to capture short-term investments and R&D spending to reduce the costs of carbon-free technology options thus helping to avoid 'technological lock-in' apparent in our present energy system and achieve compatibility with long-term stabilization targets. This advantage together with the new model formulation provides the flexibility needed to study TTP and the transfer of resources from industrialized countries to LDCs. These modeling options allow us to investigate in a systematic manner the merits of renewable energy technologies, CCS, biomass options and new nuclear designs to combat global warming.

The first conclusions of this work are that TTPs appear to have the potential to reduce the costs of global mitigation efforts and thus encourage broader participation, but with an important caveat that more detailed analysis is required to understand the potential of TTPs to increase total energy demand, which may undermine climate change objectives as well as creating other challenges for supply security and long-term resource sustainability. Thus, we come to one of the other important conclusions; that

TTPs alone are not sufficient and need to be supported by other policy instruments such as carbon taxes (if not applied already to LDCs) and/or proper electricity tariffs in order to provide the proper price signals to consumers and control emissions and electricity demand while supporting the diffusion of carbon free technology in the markets.

In this context, it is worth recalling that we have only analyzed TTPs supporting energy supply technologies, and steering technology transfer towards conservation and end-use efficiency may overcome some of these difficulties. This calls for complementary analysis with a more technologically detailed model, such as MARKAL, with a full representation of conservation measures and end-use devices. The availability of these additional targets for technology support would potentially ensure that the full revenue from the carbon taxes could be applied to support new technologies (as we saw in the results, prior to 2020-2030 not all of the available support is used). Allowing for the banking of revenues is another means to more effectively support TTPs.

It seems that the costs and the associated carbon values for achieving very stringent targets, such as those consistent with the 2°C EU objective, are very high. TTPs have the potential to reduce these costs, particularly for developing countries. However, if there is insufficient political will to pursue such strong targets, TTPs still represent a potentially important tool for reaching a compromise agreement with less stringent and more feasible targets. The BTS450 and the GRS450 scenarios analyzed here provide perspectives on the implications of possible compromise scenarios (see also Fig. 5).

However, TTP have some significant advantages. Industrialized countries have the chance to profit from a global diffusion of advanced technology (see for example Figs. 11 and 12), the induced cost reduction of carbon control, and the reduction of climate damages through the arrangement of a global participation to the new Protocol. Also, the cost-free technology transfer to less developed countries increases their welfare, generating a positive feed-back mechanism of participation. LDCs will also profit from the reduction of damages related to climate change while the expected secondary benefits of carbon control related to the improvement of local environments will be significant.

Whatever the selected scenario, the TTP proposal, like every serious policy to combat global warming, needs an increased willingness to pay to avoid climate damages first by current and future generations of the industrialized world and later on, when sufficient economic growth is accumulated, by today’s less developed countries. TTPs need careful implementation of learning investments and/or subsidies in conjunction with climate measures in order to achieve the greatest benefits.

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# Appendix: A MERGE formulation with technology transfers

The formulation described below assumes an explicit definition of taxes equal to the tax level needed to satisfy a carbon concentration target. Thus, the industrialized countries will pay a carbon tax but its revenue will finance the carbon-free technology exports to less developed countries. They will profit threefold: 1) Export technology will be fabricated in R1 countries, 2) the induced cost reduction due to learning and 3) the reduced damages due to climate change due to a global participation. The less developed countries will profit from the cost-free introduction of advanced technologies, the associated know-how transfer and the reduction of damages related to climate change. Also, the expected secondary benefits of carbon control related to the improvement of local environments will be significant.

**New variables**:

$TTRX\_R1_{R2,t}$ Technology transfer payment from donor R1 country (i.e., the Annex B regions of the Kyoto Protocol) to R2 countries (i.e., the less developed Non-Annex B regions), in period t.

$SACT_{R2,t,k}$ Learning Activity; It has the dimension of energy flow (i.e., electric or for non-electric energy) supported in form of subsides to enhance learning by doing for technology k, period t, in R2.

**Equations for the TTP**:

All these SACT activity variables appear explicitly in the fuel balances and the cumulative output specification balances for electric and not electric activities they are not explicitly presented here. The remaining changes refer to the specification of the tax-revenue and the technology transfer activities and are as follows:

**Tax-Revenue**:

$$\sum_{k \in Cfree} SCL_{R2,t,k} \cdot acrf / lf \cdot SACT_{R2,t,k} \leq Ctax_{r2,t} \cdot Clev_{r2,t} + \sum_{R1} TTRX\_R1_{R2t} \quad \forall \text{ t and R2}$$

The capital transfer of all R1 regions to an R2 region and the own revenue of R2 region, if a carbon-tax is enacted in the R2 region, should be greater than the learning subsidies (SACT) in favor of carbon-free technologies in R2 region. Here SACT has the dimension of energy flow while the annualized cost of investments $SCL_{R2,t,k} \cdot acrf / lf$ defines the level of subsidy per technology. This price-subsidy corresponds to annualized cost of investments that learns (electric and non-electric technologies). This is an example of subsidy specification; clearly other modes of subsidy could be investigated aiming to support carbon free technology as much as necessary to help its market penetration. Clearly one could apply the relation above in the discounted form allowing for banking of tax revenues in supporting LDCs.

Usually the marginal cost of carbon control is much higher than the average cost of carbon control (i.e., $Ctax_t \geq \Delta Cost / \Delta Cem$) such that a sufficient revenue is collected to pay for subsidies in the early commercialization phase of carbon-free technologies in R2 countries. The model will define the appropriate penetration level of supported technologies based on the available tax revenue and the optimization procedure that maximizes the global welfare, as SACT is a control variable.

**Technology-transfer capital and the tax revenue:**

$$\sum_{R2} TTRX\_R1_{R2,t} = \sum_{R1,R2} Ctax_{r,t} \cdot Clev_{r,t} \quad \forall \text{ period t and R1}$$

Technology Transfer payment TTRX from an R1 country to all R2 countries should be equal to the total tax revenue of region R1 in a period.

The use of the economic output equation given below is defined using the proper sign in TTRX trade values. One has to account them properly also in the definition of GDP and the specification of the Negishi-weights. Thus, in the donor R1 regions the Output is used to finance exports to R2 regions while these exports are added in the GDP specification. The opposite is the case for R2 regions.

**R1 regions, Use of economic activity Output:**

The output Y is used for Consumption C, Investment I, to pay for the energy systems cost (EC), the net trade TTRX and for the technology transfers.

$$Y = C + I + EC + NTX\,(nmr) + \sum_{R2} TTRX_{R1->R2} \qquad \forall R1$$

EC accounts already for the C-taxes in R1 region. Now, the technology transfer exports (TTRX, also called learning subsidies) to R2 regions should not be deducted from the EC cost as lump-sum revenue (as it is the case with all kind of taxes in the model). Instead, they should increase the GDP of the donor region and also as exports should be included in the Negishi-weights formulation.

$$GDP_{R1} = C + I + NTX\,(trade) + \sum_{R2} TTRX_{R1->R2}$$

Thus, R1 countries will use the tax revenue to pay for technology transfer into R2, while the energy systems cost (EC) includes the extra costs of the energy system required to control their own carbon emissions and the C-tax. The regional welfare of R1 regions is decreased as consumption decreases; however, their GDP and Negishi weights are increased.

**R2 regions:**

$$GDP_{R2} = C + I + NTX\,(trade) + EC$$

As the EC of R2 regions accounts already for their C-taxes (if enacted in R2 regions), while the tax-revenue supports their own technology, it should not be deduced from the EC as lump-sum. As also the subsidized activities are coded explicitly with a zero price, this is equivalent of subtracting the subsidy cost financed by the R1 donor countries. Therefore, the original formulation of the equation describing the use of economic output remains unchanged. Obviously, this formulation increases the welfare of R2 countries as all subsidized activities have no cost and reduce the systems energy cost.