ELECTRICITY TRADE AMONG WORLD REGIONS

TRADE THEORETIC FOUNDATION OF ENERGY-ECONOMY MODELS

Nico Bauer[*], Ottmar Edenhofer, Michael Jakob
Sylvie Ludig, Michael Lüken
Potsdam-Institute for Climate Impact Research (PIK), Germany

November 14, 2008

Abstract

We introduce infrastructure investments that render possible electricity trade among world regions into a hybrid energy-economy model and we relate the results to neo-classical trade theory. The model results indicate that the trade of electricity from North Africa to Europe is only competitive in case of prudent climate mitigation policies. The electricity transmission would allow Europe to explore the huge potential of solar energy present in North Africa in exchange for goods. Regarding the theoretical foundation four policy relevant questions are analyzed using neo-classical trade theory. First, is the introduction of trade benefitting both regions at an aggregate level? The answer for the electricity importing region is clearly positive, but for the electricity exporting region it depends on the reduction of rent incomes from other resource exports that are deteriorated by the introduction of electricity trade. Second, what is the effect on macroeconomic activity in the two regions? The analytical model suggests that the exporting region's production sector decreases, but that of the importing region increases. In the analytical

---

[*] *Corresponding author:* P.O.Box , D-14412, Germany. Tel.: ++49 +331 288 2540. E-mail: nico.bauer@hotmail.com.

model this is derived by the effect on interest rates that converge, though it is not a tradable good. Third, what is the sectoral effect for the two regions? The analysis indicates that the European electricity sector would lose from the introduction of trade. The resource and emission permit exporters lose from electricity trade because the international prices are reduced. Fourth, what is the effect on trade relations of third countries that are not involved in the electricity trade? We show that the introduction of electricity trade can have positive or negative effects depending on the resource trading position of the third countries prior to electricity trade. The numerical results indicate a positive effect, though it is relatively small. The results serve as a starting point for the discussion of political barriers to implementation of such large scale infrastructure projects. The barriers are due to the negative effect on some sectors: if for example the European electricity sector loses, it would not have the incentive to invest into the infrastructure that renders possible electricity trade.

Contents

1 Introduction

Inter-continental electricity transmission is discussed as a means to mobilize the huge renewable energy potentials in order to deal with increasing scarcity of exhaustible energy carriers and to mitigate global climate change. Long-distance electricity transmission is an inevitable precondition that presupposes considerable financial means and would impose transmission losses. The techno-economic dimension of the issue is already discussed in the literature. The technological option is proven: the investment costs and the transmission losses are known from realized projects. The economic dimension is still out to be clarified. The present study is devoted to the analysis of the trade related economic dimension.

Several studies are devoted to the techno-economics of long-distance electricity transmission that is the bridge between Europe and North Africa. These studies aim at assessing the costs and necessary investments to realize this option. The authors consider the problem as one of costs and technologies. The findings are quite promising; see e.g. Czisch et al. (2001) and Trieb et al. (2006).

However, the frameworks of energy system models applied in these studies are based on optimization methods. Most commonly the objective function is a monetary cost criterion that is minimized. Costs are summed across regions and technologies. Investments and energy flows are induced, if the global cost criterion advices to do so. The models are partial equilibrium models that compute a result that fits the Hicks-Kaldor criterion.

These models do not take into account that transmission lines are infrastructure that render possible trade and that the introduction of trade is subject to the problem of improving the economic situation of some actors, but at the same time worsening that of others. These agreements are useful to gain insights into the political preferences of actors that also aim at influencing the political process known as rent seeking behavior.

Trade theory is in large part devoted to the analysis of distributional effects of trade and trade related policy instruments; see e.g. **?**) and other textbooks. Trade models consider the idea of mutual exchange of at least two goods that is coordinated by the price mechanism. These models aim at finding equilibrium prices that solve the exchange relationships and analyze the effects on the various actors as trade or related instruments are introduced. An ordinary energy system model does not represent the concept of exchange and is therefore not suitable to make statements in lines with economic trade theory.

We address the issue of inter-continental electricity trade with two different approaches. We formulate an analytical three country static general equilibrium model and analyze the effect of trade on aggregate welfare as well as factor related income distribution. The regions trade resources and consumption goods. The resource is converted into electricity, which in turn is combined with capital to produce consumption goods. Resource trade can be constrained because – for example – part is non-tradable. This leads to non-equalization of resource prices. In such situation electricity trade can complement resource trade and induce regional resource price convergence. These price changes have effects on regional consumption production and consumption and additional lead to a re-valuation of the resource and capital endowments within the regions. Electricity trade can have positive or adverse regional welfare effects. Though the model is different in structure, it reconcile various general effects that are well known in trade theory like the Stolper-Samuelson theorem. The model mainly captures the relationship between resources, capital, electricity and production. The essential point is that this structure allows for trade of the intermediate product electricity.

The second approach is to apply a numerical, multi-regional, dynamic, general equilibrium model that embeds an energy system model into a macroeconomic growth model. The model is detailed in technologies and trade of primary energy carriers; the latter being endowments of the regions. The assumptions on endowments are that Europe is scarce in renewable energy sources, that are assumed to be plentiful in North Africa. We compare cases with and without electricity trade. The cases with electricity trade consider the infrastructure investments that make possible the transmission of electricity between the two regions.

The numerical economic results are decomposed and related to different effects that quantify the qualitative results of the analytical model. It turns out that all regions gain in aggregate from the introduction of electricity trade; even those not engaged in it. Hence, the negative welfare effects that were not impossible in the analytical model do not emerge in the numerical model. However, the sources of the net effect are very different in magnitude and sign across regions. Considerable negative effects were found for the European electricity sector, the macroeconomic sector in North Africa as well as the primary energy export sectors in North Africa and the rest of the world. These sectors may have serious objections against electricity trade and would not have the economic incentive to finance the investments for electricity transmission infrastructure.

The remainder of the study is organized as follows. Sec. 2 introduces the analytical model. The numerical assessment model *ReMIND* is introduced in Sec. 3. The technological and institutional details of electricity transmission technology and electricity trade relationships is presented in Sec. 4. The research questions and scenarios are given in Sec. 5. The final Sec. 7 discusses the results and concludes.

2 The Analytical Model

This section presents the analytical model and characterizes the solution. We first introduce the regional economies and the trade relationships. In a second step we lay out three different cases for trade between the regions that are analyzed in the third step. The three cases do not cover all possible varieties that the model could consider, but they are sufficient for the sake of the present study.

Fig. 1 illustrates the model structure. The model solves for a static general equilibrium at the sectoral level with interregional trade on trade markets (indicated by ellipses). It comprises three regions (indicated by the three large rectangles) distinguished by the index r; we call the regions home h, foreign f and the third t. The regions are identical with respect to the structure of the four sectors that are represented by the small rectangles: resource, energy, consumption good production and households. Each region is endowed with resources R_r^0 and capital K_r that are the property of the household sector and supplied to the resource and the consumption good production sector, respectively (marked by the blue arrows).

The resource sector allocates the R_r^0 to domestic supply R_r and net resource exports R_r^X (marked by the red arrows at the bottom). The net export of all regions has to equal zero: $\sum_r R_r^X = 0$. The amount of resources available in a region is:

$$R_r = R_r^0 - R_r^X \quad \forall\, r. \tag{1}$$

The electricity sector uses the resource to convert it into electricity E_r^0

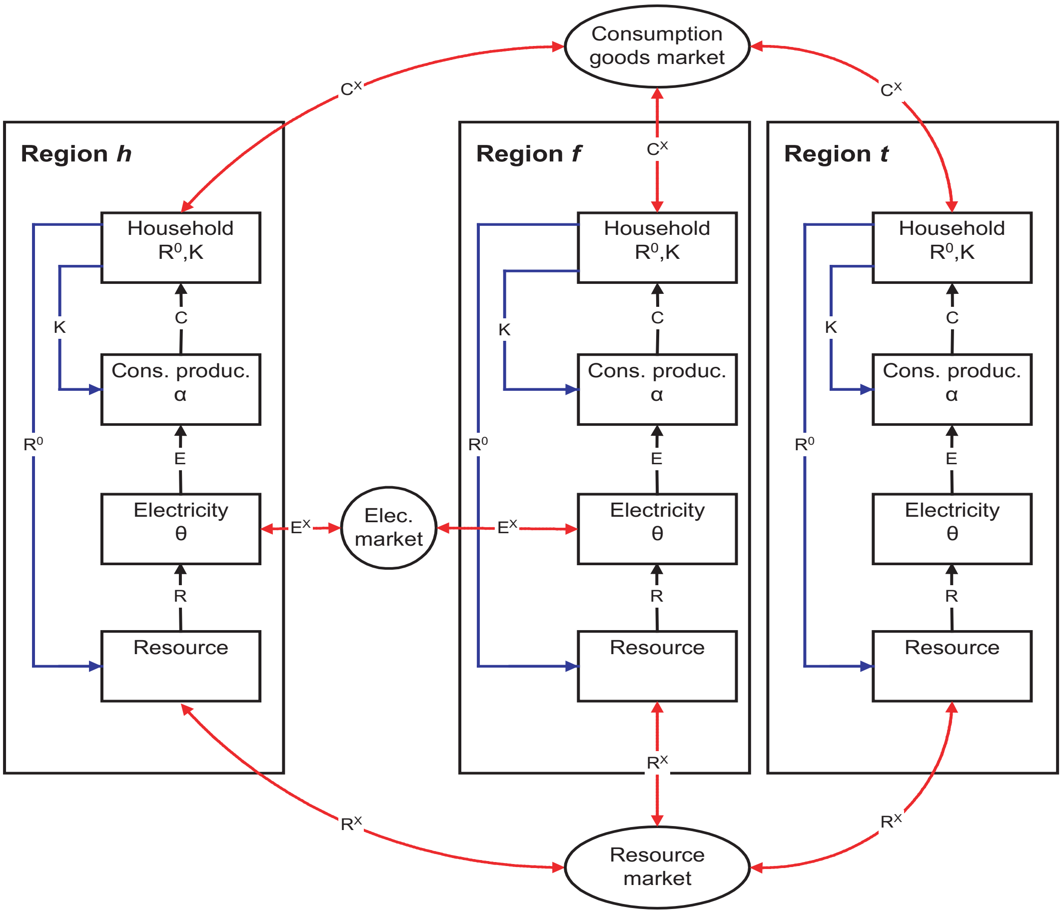


Figure 1: Structure of the analytical model.

using a linear production technology that is the same for all regions:

$$E_r^0 = \theta R_r \quad \forall\, r. \tag{2}$$

Electricity can be traded between the regions h and f. The net exports of electricity (red arrows in the middle) of both regions sum up to zero: $\sum_{r=h,f} E_r^X = 0$. The amount of electricity available in each region is:

$$E_r = E_r^0 - E_r^X \quad \text{for } r = h, f. \tag{3}$$

The consumption good sector combines capital K_r and E_r using an ordinary Cobb-Douglas production function that is the same in each region in order to produce the consumption good:

$$C_r^0 = K_r^\alpha E_r^{1-\alpha} \quad \forall\, r. \tag{4}$$

Consumption goods can be traded. Again the net exports (red arrows at the top) summed over all regions equal zero: $\sum_r C_r^X = 0$. The amount of consumption goods available in each region is:

$$C_r = C_r^0 - C_r^X \quad \forall\, r. \tag{5}$$

The household sector maximizes its consumption that is financed from its income that it receives from supplying R_r^0 and K_r. The prices of consumption goods are normalized to one in all regions. The prices for resources and electricity in each region are p_r^R and p_r^E. Below, we consider the case some regions are subject to a constraint on the share of net resource exports σ_r. If the constraint is binding, the price of the tradable part is the world market price p^R and the price of the non-tradable part is the regional price p_r^R. Hence, the budget equation in the regions are:

$$C_r = \sigma_r p^R R_r^0 + (1 - \sigma_r) p_r^R R_r^0 + p_r K_r \quad \forall\, r. \tag{6}$$

Each region is subject to a balance of payment (BOP) that equates the sum of net export values of the traded goods. The net exports are valued with world market prices that do not necessarily coincide with the prices payed within the regions. The BOP is:

$$C_r^X + p^R R_r^X + p^E E_r^X = 0 \quad \forall\, r. \tag{7}$$

Next, the different cases of trade and endowments are introduced:

1. ***Autarchy***: No trade is considered. The case is not considered in detail. The model framework allows us to isolate the autarchy outcome.
2. ***Foreign exports resources***: We assume that home and third are identical with respect to endowments. Both are well equipped with capital, but short in resources. Foreign is well endowed with resources, but short in capital.
    (a) *Full resource trade*: All resources can be traded without any restriction. No electricity trade is allowed.
    (b) *Restricted resource trade*: The resource rich region is subject to a constraint on the share of resource exports σ_r. No electricity trade is considered.
    (c) *Restricted resource trade and electricity trade*: Like case 2(b), but electricity trade is allowed between h and f.

3. ***Foreign and third export resources***: Foreign and third are identical. They have abundant resources but only little capital. Home is short in resource, but well endowed with capital.
    (a) *Full resource trade*: Like 2(a).
    (b) *Restricted resource trade*: The resource trade restriction is applied to foreign and third.
    (c) *Restricted resource trade and electricity trade*: Like case 3(b), but electricity trade is allowed between h and f.

The restriction on resource trade can be justified in two ways. First, there are physical constraints that make a share of the resource a non-tradable good. Second, the supply is reduced in order to generate higher rent incomes; however the rationale for setting σ is not endogenous. The former reason reflects the property of solar energy sources that cannot be traded like fossil energy carriers. Anyways, restrictions on resource trade will lead to rents for the resource rich regions, if the constraint is binding. Hence, the domestic resource price of the resource rich regions will be lower than the world market price. Introducing electricity trade opens up the opportunity to circumvent the restriction. Hence, the rent income will deteriorate.

2.1 Foreign Exports Resources

A preliminary note is useful. Since the regions h and t are identical, in case 2(a) and 2(b) it is enough to analyze only the two regions h and f. The result for h and t are identical in turn.

In the case of full resource trade all regional resource prices will equalize to the world market price p^R. Efficiency in production requires the following first-order-condition for resource use of the consumption good sector:

$$p^R = \frac{\partial Y_r}{\partial E_r}\frac{\partial E_r}{\partial R_r} = (1-\alpha)K_r^\alpha \theta^{1-\alpha} R_r^{-\alpha} \quad \forall\, r. \tag{8}$$

We equate the efficiency conditions of the two regions h and f and consider that $R_h^X = -\frac{1}{2}R_f^X$:

$$\frac{K_h}{K_f} = \frac{R_h^0 + \frac{1}{2}R_f^X}{R_f^0 - R_f^X}. \tag{9}$$

To ease the notation we introduce the ratio of initial resource and capital endowments $\rho = \frac{R_h^0}{R_f^0}$ and $\kappa = \frac{K_h^0}{K_f^0}$, respectively. Manipulating the above expression provides an expression for foreigns net resource exports:

$$R_f^X = \frac{\kappa - \rho}{\kappa + \frac{1}{2}} R_f^0. \tag{10}$$

The ratio on the right hand side is the net resource export share of f that we denote σ_f. The net resource export share of h is $\sigma_h = \frac{-\sigma_f}{2\rho}$. Hence, foreign's resource use is $R_f = (1-\sigma_f)R_f^0$. Eq. 10 fits with the conjecture above because foreign will export, if it is relatively well endowed with resources but relatively short in capital:

$$R_f^X \gtreqless 0 \quad \Leftrightarrow \quad \rho \lesseqgtr \kappa. \tag{11}$$

We can now determine the world resource market price using the efficiency condition of foreign Eq. 8 and the regions' resource endowments:

$$p^R = \underbrace{(1-\alpha)K_r^\alpha \theta^{1-\alpha} R_r^{0(-\alpha)}}_{\text{autarchy price in } r}(1-\sigma_r)^{-\alpha} \quad \forall\, r. \tag{12}$$

The resource price in a region is higher (lower) compared to the autarchy case, if it exports (imports) resources. The deviation depends on the export share and the capital share.

We derive the production of consumption goods in all regions:

$$C_r^0 = \underbrace{K_r^\alpha \theta^{1-\alpha} R_r^{0(1-\alpha)}}_{\text{autarchy production in } r} (1-\sigma_r)^{1-\alpha} \quad \forall\, r. \tag{13}$$

Domestic production is lower (higher) compared with the case of autarchy, if the region exports (imports) resources. Next, we determine the value of foreign's imports of the consumption good by making use of the BOP in Eq. 7:

$$-C_r^X = p^R R_r = (1-\alpha)K_r^\alpha \theta^{1-\alpha} R_r^{0(1-\alpha)}(1-\sigma_r)^{-\alpha}\sigma_r \quad \forall\, r. \tag{14}$$

Using the budget equation Eq.6 and substituting the results of Eq. 12 – 14 in order to find the consumption in each region:

$$C_r = \underbrace{K_r^\alpha \theta^{1-\alpha} R_r^{0(1-\alpha)}}_{\text{autarchy cons. in } r} \left[(1-\sigma_r)^{1-\alpha} + (1-\alpha)\sigma_r(1-\sigma_r)^{-\alpha}\right] \quad \forall\, r. \tag{15}$$

The term in square brackets is the gain of trade factor in region r denoted with $\mathcal{G}_r$. It is larger than one, if trade occurs; i.e. $\sigma_r \neq 0$. The resource exporting region uses the revenues to import consumption goods. It produces consumption goods indirectly by employing the better production technology of the resource importing region. In turn the resource importing region can increase its production, though part of the higher output is required to finance the imports. In summary, trade is mutually benefiting for the regions compared with the case of autarchy.

A final note about the effect of resource trade on the regional interest rates is useful. Larger endowments with capital imply lower interest rates in the resource importing regions compared to the exporting region in case of autarchy. Resource imports imply – in accordance with the properties of neoclassical production functions – higher interest rates, because the available capital would increase in its marginal productivity. Hence, the convergence in regional resource prices comes with a convergence of interest rates. This finding is a variant of the general statement of the Stolper-Samuelson theorem: trade increases (decreases) the price of the production factor that is relatively abundant (scarce); see e.g. Krugman and Obstfeld (2003, p. 69). This implies redistribution of income between factors favoring capital in resource importing regions and resources in the resource exporting regions, but at the expense of the resource importing regions and capital in the resource exporting region.

Now, we turn to case 2(b) introducing the bound ϵ on the resource export share of foreign. We assume that ϵ is sufficiently small so that it indeed constrains trade. In this case the regional prices of the resource would not converge to a common world market level. The regional resource prices would be:

$$p_r^R = (1-\alpha)K_r^{\alpha}\theta^{1-\alpha}R_r^{0(-\alpha)}\left(1+\frac{\epsilon}{2\rho}\right)^{-\alpha} \quad \text{for } r = h, t; \tag{16}$$

$$p_f^R = (1-\alpha)K_f^{\alpha}\theta^{1-\alpha}R_f^{0(-\alpha)}(1-\epsilon)^{-\alpha}. \tag{17}$$

The resource exporting region f would export resources at the higher price of the other two regions, which would generate a rent from resource exports. The non-tradable part of the resource is supplied domestically at a price lower than the export price. The gains of trade are different to the case without the export constraint:

$$\mathcal{G}_f^{2(b)} = (1-\epsilon)^{1-\alpha} + \epsilon\kappa^{\alpha}(1-\alpha)(\rho+\frac{\epsilon}{2})^{-\alpha}; \tag{18}$$

$$\mathcal{G}_r^{2(b)} = (1+\frac{\epsilon}{2\rho})^{1-\alpha} - \frac{\epsilon}{2\rho}(1-\alpha)(1-\frac{\epsilon}{2\rho})^{-\alpha} \quad \text{for } r = h, t. \tag{19}$$

For the resource importing region h it always holds that the gains of trade in case 2(b) are lower than in the case 2(a); i.e. h always prefers free resource trade. The situation is different for the resource exporting region f. There is always a $0 < \epsilon < \sigma_f$ that maximizes $\mathcal{G}_f^{2(b)}$. Hence, starting from the export share realized in the case of full resource trade the resource exporting region can improve its gains of trade by unilaterally constraining resource exports. However, the gains of trade reach a maximum and would then fall below the gains of trade in the case of full trade. For increasingly strict export constraints, the gains of trade would approach the value one, that is equivalent to the autarchy case. For a proof of this proposition the interested reader is referred to Appendix A of this paper.

Like above, we add a note regarding the regional interest rates. Since resource imports are lower than in case 2(a) the interest rates are lower in the resource importing countries. The effect in the resource exporting region is the opposite.

Next, we analyze case 2(c) with the restriction on resource trade but with electricity trade between h and f. In order to ease the analysis we assume that the export constraint is not so strong that it is constraining the resource exports to t in case that resource imports of h equal zero. With this assumption we exclude resource trade between h and t, which is not the aim of the present analysis.

If electricity is traded freely between h and f electricity prices equalize between both regions $p_h^E = p_f^E$. Electricity and resource prices are interrelated by the conversion process:

$$p_r^E = \theta p_r^R \quad \forall r. \tag{20}$$

From this follows that the resource prices also equalize in all regions. Therefore, the gains of trade in case 2(c) and 2(a) are the same. The trade in electricity is a substitute for the trade in resources. Owing from the results above the gains of trade in h increase, but those in f would decrease, as long as the export constraint is sufficiently weak. For very strong export constraints the effect can indeed be positive. We will come back to this point below.

If the export constraint is considered a natural barrier it enables trade of the non-tradable part of the resource in form of electricity. The owners of the non-tradable part would improve their situation from increasing resource prices because they can export the electricity generated from the non-tradable resource. However, the owners of the tradable part of the resource lose rent income because the resource price decreases towards the common world market level. The distributional effects in the resource exporting country are quite similar to the well-studied issue of export quotas; see e.g. Krugman and Obstfeld (2003, p. 252-4).

In case 2(c) domestic electricity production in h decreases compared to cases 2(a&b), because the region would only convert the domestic resource into electricity. However, electricity consumption increases because the region imports the electricity. The higher availability of electricity decreases its price and increases the interest rate. Hence, the domestic resource owners would lose due to lower resource prices, but the capital owners would gain due to the electricity imports.

The region t gains from the trade of electricity between regions h and f. The resources available from f can now be completely imported. The lower resource prices increase domestic electricity production and improve the position of capital owners. However the decreasing resource prices would deteriorate the income of resource owners. In sum, the region would benefit from increased total consumption.

We return to the gains of trade in f that are lower in case 2(c) than in 2(b), if the export constraint is not excessively strict. The model framework is subject to a shortcoming: The resource use in all regions is the same in all three cases. It is reasonable in the subject at hand that the introduction of electricity trade would increase the availability of the non-tradable part of the resource in f. The rationale is that without trade large parts of the resource are left to lie fallow. The demand from h improves the economic value and part of the fallow are made accessible to economic activity. We can analyze this effect within the framework by forming the derivative of $\mathcal{G}_f^{2(c)}$ that is related to the resource export with respect to σ_f:

$$\frac{\partial \mathcal{G}_f^{2(c)}}{\partial \sigma_f} = (1-\alpha)(1-\sigma_f)^{-\alpha}\left(1+\frac{\alpha\sigma_f}{1-\sigma_f}\right) > 0. \tag{21}$$

This expression implies that, if region f can increase the resource after the introduction of electricity trade – without decreasing the domestic use of resources – the gains of trade would unambigouosly increase. This effect potentially works against the decrease of the gains of trade that we derived above. The net effect depends on the relative weights that are subject to parameter assumptions.

2.2 Foreign and Third Export Resources

In the following we treat the case in which the regions f and t are identical. They are assumed to be relatively well endowed with resources and relatively short in capital, which leads both to export resources to region h. The following analysis focuses on the effects on region t, when electricity trade is introduced.

The gains of trade for the regions h and f in the case 3(a) are equal to those in case 2(a), that were proven to exceed one. If the resource exporting regions are considered to constrain the exports to a fixed level $\epsilon < \sigma_{f/t}$ being identical for both their gains of trade:

$$\mathcal{G}_r^{3(a)} = (1-\epsilon)^{1-\alpha} + (1-\alpha)\kappa^{\alpha}\epsilon(\rho - 2\epsilon)^{-\alpha} \quad \text{for } r = h, f. \tag{22}$$

This is structurally similar to case 2(b). The only difference is that now two regions compete for the demand of one region. There will also emerge a differnce in the resource price between the regions: the domestic resource prices in f and t are lower than the world market price that will prevail in the importing region h.

For the case with electricity trade between h and f we assume $1 + \epsilon > 2\sigma_{f/t}$ in order to exclude complicated cases of re-exports. The introduction of electricity trade will now lead to equalization of the domestic resource prices to the common world market level. The region f would use part of the non-tradable resource that is converted to electricity that is exported to region h. Hence, electricity imports from f substitute resource imports from f. Hence, the sectors of tradable resource in the two well-endowed regions lose as does the resource sector in the region h, but the value of the non-tradable resource increases.

This means that the effect on the region t from the introduction of electricity trade between h and f depends on t's resource relative endowment, thus the sign of net exports. If region t is a net exporter of resource, the decreasing international resource price due to the introduction of electricity trade decreases the rent income from the tradable part of the resource. The effect is opposite, if t is a resource importer, because then it profits from the decreasing international resource prices.

3 The *ReMIND* Model

In this Section the model *ReMIND* is at first introduced without electricity trade. The techno-economic and institutional details of electricity trade are presented in the following Sec. 4.

ReMIND is the acronym for Regional Model of Investment and Development; see also Leimbach et al. (2008). It is a global multi-regional model of the economy, the energy system and the climate system. Nine world regions[1] are represented that are interacting via trade in various goods and emissions that contribute to global warming. The regions are the agents within the model framework. The market equilibria within the regions are computed by making use of the equivalence of the social optimal solution with the decentral market solution. Between the regions a Pareto-equilibrium is computed, which will be explained below.

Within each region a social intertemporal welfare function is maximized. It depends on consumption that in turn is the residual of the economy wide income – measured in market exchange rates – after accounting for savings and variable costs of the energy sector. Savings are allocated on the capital market to the macroeconomic capital stock and investments into stocks of the various technologies in the energy sector. Among the technology alternatives there are some that only make sense in case of climate change mitigation policies; espec. technologies with carbon capture and sequestration (CCS). The generation of income requires capital and labor as well as energy that demands financial and primary energy carriers for its production.

The three sub-models are integrated by a hard-link. This means a single optimization problem is solved taking into account all constraints and interrelationships that characterize the sub-systems. The hard-link between the energy sector and the macro-economy guarantees simultaneous equilibria on the capital and energy markets. The energy market equilibrium is characterized by the price that equals demand and supply of energy in physical units. The capital market equilibrium is characterized by the interest rate that equals demand and supply for financial means. Moreover, the own rate of return of the macroeconomic capital stock and for all alternative energy technologies that are competitive equal the interest rate. If the own rate of return for an investment alternative falls short of the economy wide interest

---

[1] UCA (USA, Canada, Australia), EU-27, Japan, Russia, Middle East and North Africa, China, India, Africa, Rest of the World.

rate, this alternative is not competitive. The simultaneous capital and energy market equilibrium implies efficient – i.e. cost minimal – allocation of investments. For a more detailed analysis of the hard-link see Bauer et al. (2008).

The regions trade primary energy carriers (coal, oil, gas and uranium), emission permits and a generic good. The balances of payments are not required to be settled in every period. A region can temporarily accumulate net-debt, though at the end of the models time horizon in 2150 the net-debt has to equal zero.

Trade in the various goods takes place in a completely integrated world market. Demand and supply prices equalize at a common world market level. The concept of a completely integrated world market is best illustrated by the picture of a common pool to which exporters deliver goods and are rewarded at a common price that they cannot influence. Importers take goods from the pool at the same price. Equilibrium means that exports and imports equalize. This is going to be different in the case of electricity trade because the common pool does not exist anymore, but trade requires investments into transmission lines in advance in order to transport electricity from one region to another.

The solution for the trade equilibria is computed by the Negishi approach that allows for the use of optimization algorithms; see Negishi (1972). The method guarantees a Pareto equilibrium between all regions that is characterized by a set of price paths that equal supplies and demands for the traded goods. This reflects the economic idea of exchange: a region exports a good, if and only if it receives sufficient imports of another good in turn. The equilibria on the trade markets guarantee efficient – i.e. cost minimal – use of the endowments and production technologies. Endowments can either be due to natural conditions like in the case of natural resources or they are subject to political agreements as in the case of emission permits. In both cases it is important to note that the efficient allocation induced by the trade equilibrium is consistent with the second theorem of welfare economics: the efficient allocation of goods on the market is separable from the distribution of the initial endowments, if markets work efficiently. This means that – assuming efficient markets – no special emphasis has to be put on the particular institutional framework of an international climate mitigation framework except for the stabilization goal, if one aims at analyzing the global costs of climate change

		Primary energy types						
		Exhaustible				Renewable		
		Coal	Crude oil	Natural gas	Uranium	Solar, wind, hydro	Geo-thermal	Biomass
Secondary energy types	Electricity	PC*, Oxyfuel, IGCC*, CoalCHP	DOT	GT, NGCC*, GasCHP	LWR	SPV$^{\#}$, WT$^{\#}$, Hydro	HDR	BioCHP
	Hydrogen	C2H2*		SMR*				B2H2*
	Gases	C2G		GasTr				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Transport fuels	C2L*	Refinery					B2L*, BioEthanol
	Other liquids		Refinery					
	Solids	CoalTR						BioTR

Table 1: Overview on primary and secondary energy carriers, and the alternative conversion technologies represented in *ReMIND*.

Abbreviations: PC - conventional coal power plant, Oxyfuel - oxyfuel, IGCC - integrated coal gasification combined cycle power plant, CoalCHP - coal combined heat and power, C2H2 - coal to hydrogen, C2G - coal to gas, CoalHP - coal heating plant, C2L coal to liquids, CoalTR - coal transformation, DOT - diesel oil turbine, GT - gas turbine, SMR - steam methane reforming, GasTR - gas transformation, GasHP - gas heating plant, LWR - light water reactor, SPV - solar photovoltaic, WT - wind turbine, Hydro - hydroelectric power plant, HDR - hot dry rock, GeoHP - heat pump, BioCHP - biomass combined heat and power, B2H2 - biomass to hydrogen, B2G - biogas plant, BioHP - biomass heating plant, B2L - biomass to liquid, BioEthanol - biomass to ethanol, BioTR - biomass transformation.

* this technology is also available with carbon capture and sequestration (CCS).

$^{\#}$ this technology is characterized by technological learning.

mitigation; see e.g. Manne and Stephan (2004). This will remain valid, when we are going to introduce electricity trade below.

The model represents energy conversion technologies with respect to essential economic and engineering characteristics. The primary energy demand and CO_2 emissions are determined by capital structure of conversion technologies. Emission mitigation is achieved by restructuring the capital stock or by changing the demands for secondary energy carriers. The emissions of CO_2 could be reduced through these two reallocation mechanisms or by investing in carbon capture and sequestration, which increases the capital costs and reduces efficiency. Tab. 1 summarizes the alternative routes and technologies for converting primary into secondary energy carriers.

Primary energy carriers are either exhaustible or renewable. The former are characterized by extraction costs that are increasing with cumulative usage, while the latter are subject to a constraint on annual production potential that is differentiated by various grades. The harvest of biomass leads – additionally – to costs that are accounted for in the budget constraint of the economy.

4 Long Distance Electricity Transmission

This section deals with the electricity transmission lines that render possible trade. In Sec. 4.1 the techno-economic literature of long-distance electricity transmission is reviewed and the essential parameter values are identified and uncertainty ranges are delimited. In Sec. 4.2 the institutional aspects and the chosen setting is introduced.

4.1 Techno-Economic Assessment

To allow long-distance electricity transmission in the *ReMIND* model, a new technology was implemented in the Energy System module. A literature assessment resulted in the selection of the relevant input parameters.

In Czisch et al. (2001) the distance between different regions in Northern Africa and Europe (the German city of Kassel is chosen as ending point of the transmission line) is estimated to be about 3000 km. May (2005) analyzes three different routes with lengths between 2700 km and 4000 km. In the TRANS-CSP report (Trieb et al. (2006)) for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, two routes with about 3100 km and one of more than 5000 km are evaluated. To get a general view on the potential of electricity trade over transmission lines, we chose to study a transmission line of 3000 km.

The technology used for long-distance electricity transmissions is High Voltage Direct Current (HVDC). HVDC allows transmission on overhead lines, underground cables and sea cables. Losses are significantly lower than with AC power for transmission over long distances. HVDC converter stations may have higher investment costs than AC transformers, however, compensation of inductive and capacitive losses for long-distance AC is costly and complex so that a break-even distance of 50-100 km between the two technologies can be assumed; see e.g. Rudervall et al. (2000)).

The transmission efficiency of HVDC lines is relatively high, as May (2005, p. 35) shows. The losses depend on the voltage and length of the line and range from 2.5 %/1000 km for a 800 kV line to 6 %/1000 km for a 500 kV line. This corresponds to 7.5 % to 18 % for a line of 3000 km. For a first assessment, we chose an efficiency of 90 %.

This analysis of electricity trade between Europe and Northern Africa is limited to the consideration of HVDC lines, it is clear, however, that an actual installation of larger transmission capacities would make use of existing DC and AC infrastructure as described for example in May (2005) and Trieb et al. (2006).

As most present HVDC-projects are specially designed for the local geographic and political situations, their investment costs are difficult to compare. Data found in the literature and in official project descriptions ranges from 260 $/kW (May (2005)) to 3575 $/kW (NorNed project description[2]) for a cable of 3000 km. It is important to consider that location of the cable (i.e. overhead line, underground cable, shallow or deep water submarine cable) and political circumstances (crossing of different countries, necessity of building permits...) have a very strong influence on project costs.

We chose to use the values from the TRANS-CSP report (Trieb et al. (2006)) for our study as they describe electricity transmission between the same regions than implemented in our electricity trade analysis, namely Europe and Northern Africa. Thus we implemented investment costs of 450 $/kW

---

[2] `http://www.tennet.org/english/projects/norned_/projectomschrijving.aspx`, retrieved on 25.06.2006

Input Parameter	Value Range	Reference
Investment costs (3000km, HVDC)	260 $/kW	May (2005)
	450 $/kW	Trieb et al. (2006)
	3575 $/kW	Homepage of the NorNed Project (see footnote 2 on page 19)
Learning Rate	38%	Junginger et al. (2004), Peeters (2003)
Efficiency	82% - 92,5%	May (2005)

Table 2: Input parameters

for a 3000km line.

In his assessment of cost reduction prospects for offshore wind farms, Junginger et al. (2004) points out that larger numbers of HVDC projects could lead to a higher degree standardization for cables and converter stations and thus to a significant decrease in investment costs. An investigation by Peeters (2003) uses data from existing projects and develops an experience curve. A learning rate of 38 % is determined. A problem of this study was the small amount of data available and most cost informations did not include laying of the cables which can strongly influence final investment costs. However, considering the little current standardization and the probability of a large number of offshore wind projects in the near future, it can be assumed that a rapid decline in costs for HVDC projects is possible.

As very little data was found on experience curves for transmission lines, we chose to use the values investigated by Junginger et al. (2004) and Peeters (2003).

4.2 Institutional Setting

The institutional setting characterizes the actions of the regions, at which point of the trading process the property rights are transferred and what prices are paid. The characterization is of interest here because the model solves for a Pareto-solution between the regions and the institutional setting affects the trading relations between the regions.

The investments for the transmission infrastructure add to the energy system costs of Europe. Electricity that is delivered from MENA is rewarded with the local price in MENA; i.e. it is a free on board contract. The transmission of a unit of electricity is therefore subject to the transmission losses and the costs for transmission.

The installation of electricity generating facilities is always domestic. The possibility of foreign direct investments is not considered. However, MENA could borrow financial means from Europe to finance the investments.

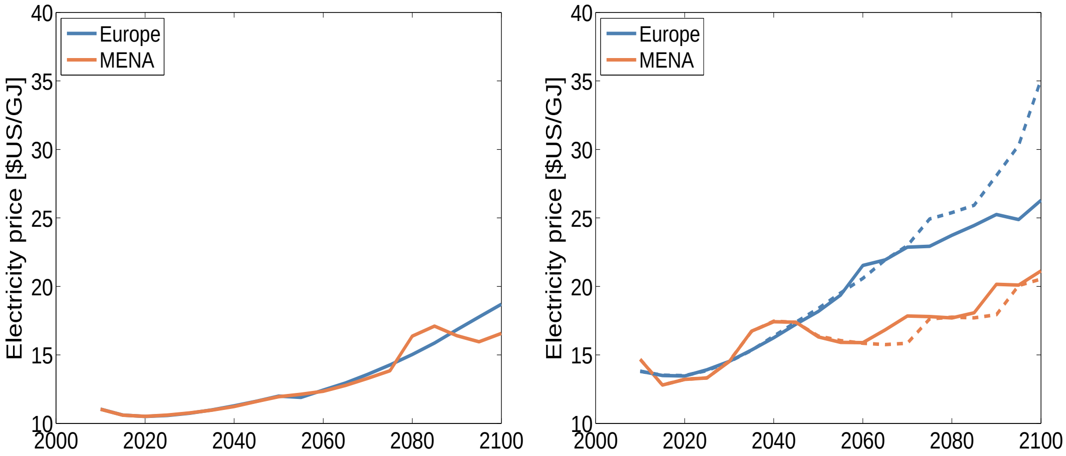
The MENA region is not allowed to exercise oligopolistic market power on the markets for primary energy. Hence, prices differences are only justified by reasons of costs and technology.

5 Scenarios and Research Questions

With the *ReMIND* model we compare two scenarios of climate change mitigation policies. First, we compute a business as usual scenario (BAU) without any effort to mitigate climate change. For the second scenario (POL) we impose a climate change constraint that does not allow global mean temperature to increase by more than 2°C above the pre-industrial level. The emission permits are distributed according to convergence and contraction towards equal per-capita emissions and all emission permits are fully tradable. For each of these scenarios we compute a variant without (BAU, POL) and with (BAU^+, POL^+) the option to trade electricity between Europe and MENA.

Regarding electricity trade two policy relevant questions are analyzed and we relate the numerical results (Sec. 6) to the qualitative insights of the analytical model (Sec. 2):

1. Is prudent climate change mitigation policy a pre-requisite for inducing electricity trade and how does it change the regional production and consumption as well as the electricity prices?
2. Is the introduction of trade benefitting both regions at an aggregate level? To answer this question we focus on the changes in consumption due to the introduction of electricity trade.
3. What is the sectoral effect for the two regions? The change in sectoral outputs and production factors are studied
4. What is the effect on trade relations of third countries that are not involved in the electricity trade? We will analyze the effects also for the third countries that are aggregated to a rest-of-the-world (ROW) region.



(a) BAU scenario (b) POL & POL$^+$ scenarios

Figure 2: Electricity prices in Europe and MENA for the BAU and the POL&POL$^+$ scenarios, with interregional electricity trade (solid line) and without (dashed line). *Nota bene:* the reason that the prices do not fully converge is due to cost factors and not because of the use of oligopolistic market power as was described above.

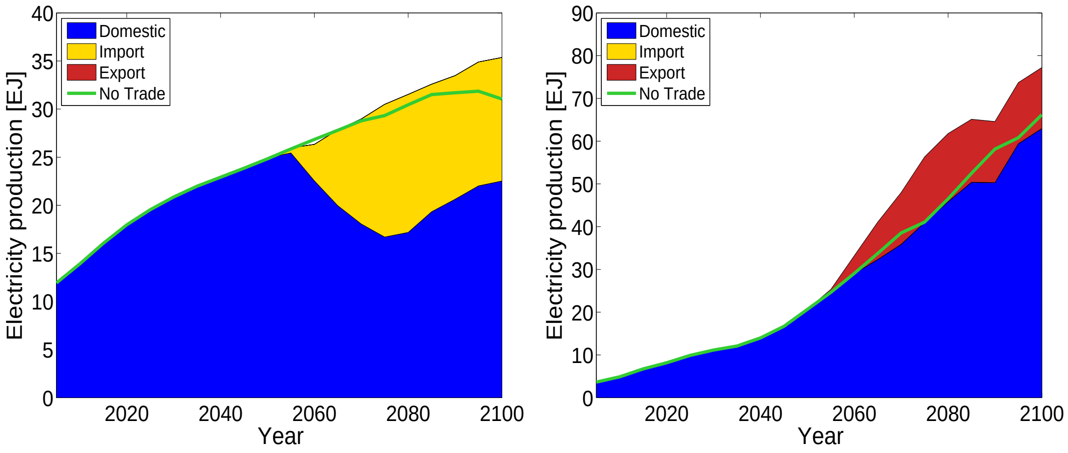
We discuss the findings with respect to the insights we gained from the analytical model.

6 Results

The first of the above questions asks for the significance of climate change mitigation policies for triggering electricity trade. It turns out that the case without climate protection constraint does not induce electricity trade, because the electricity price differences in the two regions are negligible. However, the imposition of a climate change constraint would lead to remarkable and growing price differences between the two regions.

Fig. 2 shows the development of the prices. Fig. 2(a) indicates for the BAU scenario that the price differences are not sufficiently large to induce trade. For the POL scenario instead the prices would diverge; see Fig. 2(b). This is mainly due to Europe's small endowments with renewable energy sources that become more and more pressing. Allowing for the possibility of electricity trade in the case POL$^+$ leads to partial price convergence. The remaining gap is due to the 10% transmission losses and because of the infrastructure costs.

The price development is reflected in the production, consumption and



(a) Europe

(b) MENA

Figure 3: Electricity production and trade in the two policy scenarios.

trade flows of electricity in the two regions. Fig. 3 shows the production of electricity in the POL scenario (green line). In the POL$^+$ scenario electricity production in Europe decreases (blue area in Fig. 3(a)), but it is overcompensated by the imports (yellow area). Hence, Europe has more electricity available at lower prices.

Fig. 3(b) shows the effects for MENA. The production of electricity increases (blue plus red area), but part would go into export (red area). Domestic consumption (blue area) is slightly lower than in the case without electricity trade. Hence, MENA consumes less electricity at higher prices.

These effects are in correspondence with the findings of the analytical model. Moreover, the total electricity production in both regions would increase by trade. Hence, electricity trade uses more of the natural endowment of MENA that was non-tradable and left fallow. This issue was noted as a shortcoming of the analytical model and lead us to the effect considered in the derivative in Eq. 21.

In the following we use an economic decomposition analysis to answer the other questions. The decomposition computes the undiscounted cumulative differences between the cases POL and POL$^+$. The graphs indicate first of all the effect on consumption. The remaining bars explain the different sources that explain this effect. Positive (negative) values mean that the factor contributes to additional (less) means to finance consumption.[3]

---

[3] For the traded goods, which are indicated by green-yellow toned colors, this combines the

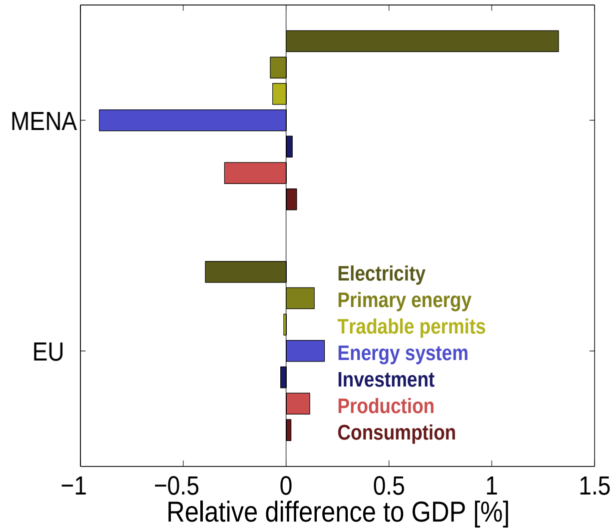


Figure 4: Decomposition of the budget equation and the inter-temporal balance of payments (BOP) for the regions Europe and MENA. The abscissa shows the cumulative differences of the case with and without trade over the period 2005 – 2105 relative to the GDP in the case without trade.

Fig. 4 presents the decomposition analysis for the regions Europe and MENA. It shows that the effect on consumption is positive for both regions, thus, the introduction of electricity trade is mutually benefittial. Since MENA is not allowed to exercise oligopolistic market power as discussed above, it is not possible that it suffers from a reduction of rent incomes from strategically constraining the resource supply.

The effect on macroeconomic activity measured in terms of GDP differences in the two regions is of opposite sign. Europe increases production because it has more electricity available, but MENA reduces macroeconomic output due to lower domestic electricity consumption. Hence, Europe can finance additional consumption from increased overall economic income, and *vice versa* for MENA. This comes with an increase of macroeconomic investments in Europe, which requires financial means that are not available anymore for consumption. The opposite holds for MENA. These effects are explained by the analytical model. The effect on investments is corollary to the effect on interest rates noted in that context: increasing interest rates in Europe are an incentive to increase investments; *et vice versa* for MENA.

---

price and the quantity effects. Thus, the signs of the bars do not reveal whether price or quantity changes are the reason.

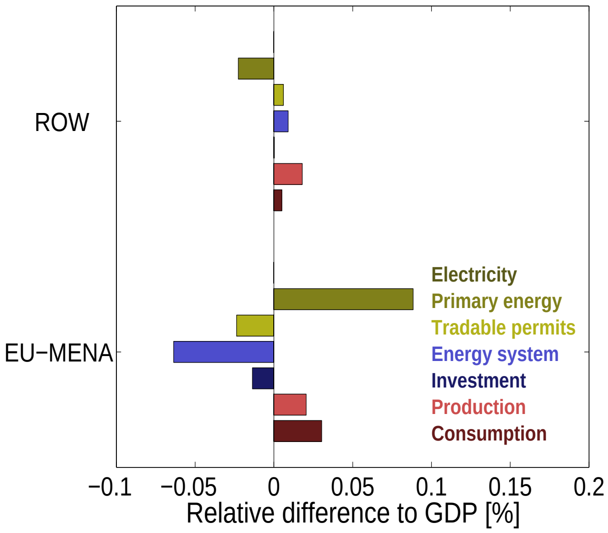


Figure 5: Decomposition of the budget equation and the inter-temporal BOP for the regions Europe and MENA. The abscissa shows the cumulative differences of the case with and without trade over the period 2005 – 2105 relative to the GDP in the case without trade.

The energy system costs in Europe are significantly decreased because of lower electricity production. The additional infrastructure costs that are contained in this effect are relatively small compared to the effect regarding generation capacities and domestic fuel production. MENA, instead, allocates more financial sources to the energy sector, since they increase the generation capacity for export.

Next we turn to the effects of traded commodities. Europe spends slightly more on tradable emission permits, but gains from less expenditures for imported primary energy carriers. The effects for MENA are negative regarding both commodities. The effects are surprisingly small. This is due to the outcome of the POL scenario in which Europe especially uses more nuclear power that it has to import from other regions than MENA. The import of electricity mainly substitutes nuclear power in Europe by electricity from solar sources. The effect on the other countries will be discussed below.

Last but not least, the effect of electricity trade is the single most important one in both regions. Europe has to finance the electricity imports (i.e. the financial flow to MENA), which is not available anymore for consumption. However, this is the source of financial means for MENA that works against the negative effects mentioned above.

Finally, we focus on the effects on the other regions. Fig. 5 shows the same economic decomposition analysis for two regional aggregates: EU-MENA is the aggregate of the two regions engaged in electricity trade and ROW (rest of the world) is the aggregate of all other regions.

The effects on ROW aggregate are relatively small. However, consumption and GDP are increased, which implies that third countries not engaged in electricity trade gain at the macroeconomic level. The negative effect on primary energy due to reduced uranium imports by Europe was already mentioned above and discussed in the context of the analytical model. However, it is overcompensated by increased GDP, reduced energy system costs and a positive effect from emission permit trade. The analytical model showed that the qualitative effect on consumption was not *a priori* determined. It was also possible that it turns out to be negative.

For the EU-MENA aggregate we observe that consumption and GDP are both increasing, though increasing GDP requires more investments in macroeconomic capital. Moreover, the effects on energy systems costs and trade of primary energy indicate that electricity trade induces a substitution process in the energy sector towards capital intensive technologies reducing the expenditures for primary energy.

7 Discussion and Conclusions

The study of brought together the issue inter-continental electricity transmission and economic trade theory. The analysis was performed in an analytical and a numerical model framework. The analytical trade model indicated various adverse effects at the sectoral level that could even add up to negative effects at the aggregate regional level. The analytical model was used to identify the qualitative effects on the regional and sectoral levels that could be expected from numerical model results.

The numerical results of introducing electricity trade into a model with strong climate change mitigation policies were in line with the expected results. And it turned out that all regions would gain at the aggregate level. However, at the sectoral level the model indicated significant adverse effects. Most considerable are the negative effects on the European electricity sector, the macroeconomic sector and the resource exporting sector in North Africa as well as the resource exporting sector of the rest of the world.

These sectors may have major objections on the project, they could potentially be compensated by the winners of electricity trade. The key point – and here the study deviates from traditional analysis of trade and welfare – that the introduction of trade is not a public policy decision that can be influenced directly. The quest of trade is essentially connected to the investment of transmission lines; i.e. the infrastructure that renders possible trade.

Somebody needs to finance the infrastructure, but losers do not have the incentive to do so. One could consider the European electricity sector as the natural entity from a technological point of view. Differently, the North African resource export sectors could be considered as a group with sufficient financial means to undertake the investment. However, these sectors would lose from the introduction of electricity trade because it decreases their rent incomes.

The study therefore identified considerable economic and political barriers to the implementation of a infrastructure project that would reduce the costs of climate change mitigation for all regions at the aggregate level. The analysis shows that the policy advice regarding the introduction of electricity transmission infrastructure is not only about technology and cost parameters, but needs also to take into account the distributional effects of trade. Hence, the study provides useful insights by combining technology specific engineering based information with qualitative insights from economic trade theory.

A Appendix: Analytical proof for a maximum of $\mathcal{G}_f$

The proof is based on the Weierstraß theorem. Fig. 6 gives a sketch of the proof. The function $\mathcal{G}_f$ is assumed to be continuous. We know that for the case of autarchy $\sigma_f = 0$ the gains of trade equal one. For the case 2(b) we know that $\sigma_f > 0$ and $\mathcal{G}_f^{2(b)} > 1$. If the derivative at this position is negative we can conclude that there has to be at least one maximum, though the exact value of σ_f maximizing $\mathcal{G}_f$ is not determined. Hence, the task is to determine the sign of this derivative. If it is negative we conclude that there must exist a maximum. Without loss of generality we assume $\kappa > 1$.

The derivative of $\mathcal{G}_f$ taken from Eq. 18 at the location $\sigma_f^{2(b)}$ is:

$$\frac{\partial \mathcal{G}_f}{\partial \sigma_f}\Big|_{\sigma_f=\sigma_f^{2(a)}} = (\alpha-1)(1-\sigma_f)^{-\alpha} + \kappa^{\alpha}(1-\alpha)\left(\rho + \frac{\sigma_f}{2}\right)^{-1-\alpha}\left(\rho + (1-\alpha)\frac{\sigma_f}{2}\right). \tag{23}$$

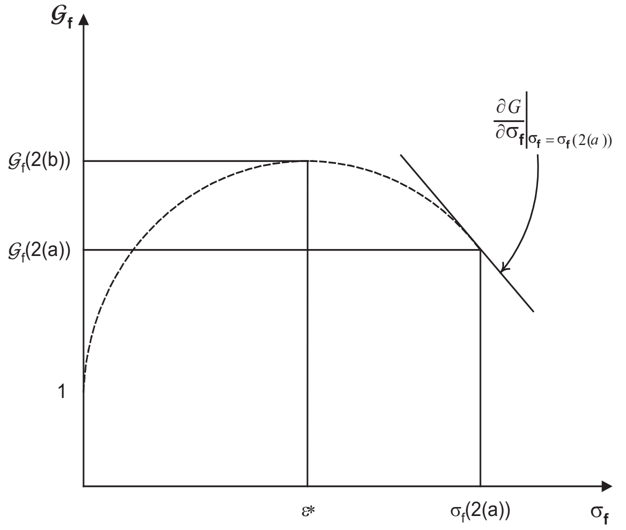


Figure 6: Sketch of the proof for a maximum of the function $\mathcal{G}_f$.

The sign of the derivative is negative, if the first term outweighs the second:

$$(\sigma_f - 1)^{-\alpha} > \kappa^{\alpha} \left(\rho + \frac{\sigma_f}{2}\right)^{-1-\alpha} \left(\rho + (1-\alpha)\frac{\sigma_f}{2}\right). \tag{24}$$

This expression can be simplified by standard manipulations:

$$\left(\frac{1-\sigma_f}{\kappa}\right)^{-\alpha} > \left(\rho + \frac{\sigma_f}{2}\right)^{-1-\alpha} \left(\rho + (1-\alpha)\frac{\sigma_f}{2}\right). \tag{25}$$

The left hand side is always exceeds 1, because ,$0 < \sigma_f, \alpha < 1$ and $\kappa > 1$. The right hand side is always smaller than one due to the following reasons. The term in the first parenthesis is always larger than the term in the second parenthesis. The exponent is always smaller than minus one. Hence, the right hand side is undoubtedly smaller than one. This condition determines the negative slope of the gains of trade function at the value of σ_f that emerged in case 2(a). Therefore, a unilateral reduction of exports $\epsilon < \sigma_f^{2(a)}$ would increase the gains of trade.

Continuity of the gains of trade function and the fact that the gains of trade are lower in the case of autarchy σ_f implies that there is an optimal value of ϵ that maximizes the gains of trade of the region f.

References

N. Bauer, O. Edenhofer, and S. Kypreos. Linking Energy System and Macroeconomic Growth Models. *Journal of Computational Management Science (Special Issue on Managing Energy and the Environment)*, 5:95 – 117, 2008.

Gregor Czisch, Stefan Kronshage, and Franz Trieb. *Integration Erneuerbarer Energien in Versorgungsstrukturen (Themen 2001)*, chapter Interkontinentale Stromverbünde - Perspektiven für eine regenerative Stromversorgung, pages 51–63. FSV (Forschungsverbund Sonnenenergie), 2001.

Martin Junginger, André Faaij, and Wim C. Turkenburg. Cost reduction prospects for offshore wind farms. *Wind Engineering*, 28(1):97–118, 2004.

Paul Krugman and Maurice Obstfeld. *International Economics. Theory and Policy.* Addison Wesley, sixth edition, 2003.

M. Leimbach, N. Bauer, L. Baumstark, and O. Edenhofer. Mitigation costs in a globalized world: Climate policy analysis with REMIND-R. *Environmental Modeling and Assessment*, submitted, 2008.

Alan Manne and Gunter Stephan. Global Climate Change and the Equity-Efficiency Puzzle. *Energy*, 30:2525 – 36, 2004.

Nadine May. Eco-balance of a solar electricity transmission from north africa to europe. Master's thesis, Technical University of Braunschweig, 2005. URL `http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/Ecobalance_of_a_Solar_Electricity_Transmission.pdf`.

T Negishi. *General Equilibrium Theory and International Trade.* North-Holland, Amsterdam, sixth edition, 1972.

Ad Peeters. Cost analysis of the electrical infrastructure that is required for offshore wind energy: An experience curve based survey. final report, Utrecht University, 2003. URL `http://www.chem.uu.nl/nws/www/publica/Publicaties2003/e2003-02.pdf`.

Roberto Rudervall, J.P. Charpentier, and Raghuveer Sharma. High voltage direct current (hvdc)transmission systems technology review paper. Technical report, ABB / Worldbank, 2000. URL `http://www.worldbank.org/html/fpd/em/transmission/technology_abb.pdf`.

Franz Trieb, Christoph Schillings, Stefan Kronshage, Peter Viebahn, Nadine May, and Christian Paul. Trans-mediterranean interconnection for concentrating solar power (trans-csp). Final report, DLR, 2006. URL http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/TRANS-CSP_Full_Report_Final.pdf.