Long-term CO_2 emissions abatement in the power sector and the influence of renewable power

T. Aboumahboub[1], K. Schaber[2], U. Wagner[1] & T. Hamacher[1]
[1]*Institute for Energy Economy and Application Technology, Technical University of Munich, Germany*
[2]*Research Group for Energy and Systems Studies, Max Planck Institute for Plasma Physics, Germany*

Abstract

This study investigates influences of Variable Renewable Energy Sources (VRES), i.e. solar and wind power, on the CO_2 emissions of the global electricity sector and on the certificate price. We use an energy system model based on linear programming. It may be applied to optimize capacity extensions in power generation, transport, and storage under different framework conditions. Here, long term abatement in the power sector with a special focus on the influence of VRES is studied. When a time horizon from 2020 to 2040 was taken into account, optimization results showed that wind energy is extensively employed to meet ambitious emissions reduction targets. In 2020, total wind capacity reaches 4570 GW and rises to 15285 GW by 2040; extension of wind power at this level allows limiting CO_2 emissions of the power sector to 6107 million tons in 2020- i.e. 35% reduction compared to the year 2000; it reduces to 2067 million tons by 2040, while the certificate price rises to 61 €/ton. This can only be realized if cross-border interconnections are extended far beyond the current levels. If grid extensions are not allowed, over-installation of capacities up to 18% is unavoidable to satisfy the proposed CO_2-limit in 2040. In this case, the certificate price shows a significant increase to 147 €/ton by 2040.
Keywords: renewable energy, optimization, certificate price, CO_2 emissions.

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1 Introduction

The world is facing global challenging issues of climate change. CO_2 is one of the main contributors in the global warming phenomenon; its concentration has risen from a pre-industrial level of about 280 ppmv to more than 380 ppmv Nakicenovic [1]. To ensure that carbon dioxide concentrations stabilize at target levels, significant reduction of the global emissions is required. Without near term introduction of supportive and effective policy actions by governments, energy related green house gas (GHG) emissions, mainly from fossil fuel combustion, are projected to rise by over 50% from 26.1 GtCO2eq in 2004 to 37-40 GtCO2eq by 2030 (IPCC [2]). Regarding the considerable contribution of the power sector, substantial changes must be made in its current structure. Promotion of low or no emitting technologies is of high priority. Indeed, projections of the global energy mix in macroeconomic models, i.e. integrated assessment models, which integrate GHG reduction targets, show that within the coming century a significant share of renewable energies is required to accomplish 550 ppmv and 440 ppmv emissions reduction targets; here, mostly solar and wind energy are proposed as well as biomass (Knopf and Edenhofer [3]).

In the context of long-term technological change and the potential for reducing CO_2 emissions of the power sector, studies have been conducted, focusing on national levels. In Heitman and Hamacher [4], maximum feasible abatement in the German electricity generation system in 2030 and required structural changes have been determined through applying the German electricity system model URBS-DE. Influence of the carbon price and its inherent uncertainty was studied with stochastic parameterization of the specified planning tool based on stochastic linear programming. A study has been conducted in Mathur *et al.* [5] through applying the energy planning tool MARKAL to simulate the Indian power sector for a time horizon from 2000 to 2025. The results show that besides hydro power, wind energy is an alternative solution, which becomes more and more attractive with the introduction of carbon taxes, while photovoltaic systems with the considered characteristics do not have any chance for large-scale penetration.

Here, we study influences of VRES on the CO_2 emissions abatement and the certificate price based on an elaborated methodology. Regarding the concern about the contribution of all parts of the world in an international movement towards an emission free electricity supply system, it is relevant to study this issue on the world-wide scale. Taking into account a long-term horizon from 2020 to 2040, we analyze new investments in the electricity sector, required to satisfy different global CO_2 emissions reduction targets. Influence of the possibility for extension of solar and wind power on the CO_2-certificate price and the role of international exchange are studied.

The paper proceeds as follows. In section two, the model used to simulate and optimize the electricity generation system at world-wide scale is described. Section 3 focuses on new investments, required to satisfy long-term CO_2 emissions reduction targets; influence of the possibility for extension of solar and wind power and the role of international exchange on the CO_2-certificate price are investigated.

2 The global electricity system model

To analyze impacts on the structure of the electricity generation system, imposed by the intermittency of VRES, the global electricity generation system model URBS-GLB has been developed (Aboumahboub *et al.* [6]). The model is an extension of the German electricity system model (Heitman and Hamacher [4]).

To perform the optimization, the model uses a deterministic approach based on linear programming. Model formulation and optimization process are realized with the application of General Algebraic Modeling System (GAMS) software package (Rosenthal [7]). Optimization is carried out for one typical year with hourly temporal resolution. Capacities of power generation and storage as well as inter-regional transport are determined through the optimization. The power produced by each of the power plant technologies, inter-zonal flows, CO_2 emissions, and the electricity system marginal price are determined for each region and at every hour of the simulation period. The cost of avoiding one ton of CO_2 – i.e. marginal price of CO_2 emissions – is also concluded from the optimization.

Total system costs serve as objective function and are given in eqn. (1). It falls into total investment, fixed and variable operation costs of all types of power plants, transmission lines, and energy storage facilities. The fourth sum represents the emissions costs. In eqn. (1), C describes the total installed capacity while CN represents the newly invested power production, storage, and transport technologies available at each region. E^{in} is the energy input in technology i operating in region x at time step t. $k^{\mathrm{Inv,Fix;var}}$ are the annuity of investment cost, fixed and variable costs, respectively. r represents the distance between two model regions, while z is the geometry matrix and shows the interconnection possibilities between neighboring regions. w is the weighting factor of the selected times steps to simulate one year. $kemf_i$ is the emission factor of the power plant technology i; $kCO2$ is the assumed CO_2-certificate price.

$$
\begin{aligned}
z = \sum_{x} \{ & \sum_{i \in \Pr PG} (k_i^{Inv}.CN_i(x) + k_i^{Fix}.C_i(x) + \sum_t [k_i^{Var}.E_i^{in}(x,t).w(t)]) \\
& + \sum_{i \in \Pr Tr} \sum_{y} \frac{1}{2} z(x,y).r(x,y)[k_i^{Inv}.CNTr_i(x,y) + k_i^{Fix}.CTr_i(x,y) + \sum_t k_i^{Var}.ETr_i^{in}(x,y,t).w(t)] \\
& + \sum_{i \in \Pr Sto} [k_i^{Inv}.CNSt_i(x) + k_i^{Fix}.CSt_i(x) + \sum_t k_i^{Var}.ESt_i(x,t).w(t)] \\
& + \sum_{i \in \Pr PG} \sum_t [E_i^{in}(x,t).w(t).kemf_i.kCO2e] \}
\end{aligned}
\tag{1}
$$

Overall system cost minimization is subject to restrictive equations, which describe the energy system, such as the satisfaction of electricity demand, transport and storage losses, conversion losses, technical potential of renewable energies and technical limits of different power plants (Heitman and Hamacher [4]). Zonal configuration of the model is represented in [6].

In order to evaluate technical potential of solar electricity, the global irradiation dataset produced for SeaWiFS was applied here (Bishop et al. [8]). Global data of wind velocities for on- and offshore sites was taken from World Wind Atlas [9]. The transformation from wind velocity to active power output has been done based on the characteristics of modern existing wind turbines [10]. Total capacity of renewable technologies, permissible to be installed at each model region, was determined based on the detailed analyses of global technical potential of wind energy and solar thermal electricity [6, 11, 12].

Geographically aggregated projections of the global electricity demand for the time period from 2010 to 2100 based on the B_2 scenario of International Panel on Climate Change (IPCC) has been spatially disaggregated according to the spatial distribution of population [13]. The electrical load profile for each model region was determined based on the linear combination of normalized load curves of comprising countries according to the existing data [14–16] shifted for relevant time zones.

Capacities of currently operating power plants were determined based on the UDI World Electric Power Plants Data Base [17] and projected to 2050 based on the technical life time of different power plant technologies (Roth and Kuhn [18]). As the power plants data has not been prepared as a geographically disaggregated dataset, geographic information has been extracted from the GIS-based data of Carbon Monitoring for Action (CARMA) (Wheeler and Ummel [19]). To reduce the complexity, thermal power plants were aggregated according to the main fuel. Net transfer capacities of the UCTE (Union for the Co-ordination of Transmission of Electricity) interconnected area were used to represent the existing cross-border interconnections [14]. Techno-economic parameters of power plants were determined based on the validated data (Roth and Kuhn [18] and Han and Ward [20]); fuel prices were projected based on the projections made in Roth and Kuhn [18].

3 Results

3.1 Influence of VRES on CO_2 emissions marginal price

To focus on the effect of solar and wind power, within the optimization process, it was assumed that nuclear and hydro power plants are not expandable beyond the existing levels. Installed capacities of transport and storage up to the year 2009 were set as upper capacity boundaries. According to the implemented CO_2-limit and the possibility for extension of VRES, scenarios can be classified. In first sets of scenarios, total CO_2, emitted from the global electricity sector, may only rise to 10068.92 million tons in 2025 (7% above the level of year 2000). In another sets of scenarios, the CO_2-limit was tightened. Total CO_2 emissions, in 2025, shall be lower than 5745.061 million tons (38% below the level of year 2000). In baseline scenarios, existing capacities of solar and wind power were set as upper capacity boundaries. In scenarios “REOPT-CO2H” and “REOPT-

CO2L", penetration share of solar and wind as well as their combination was determined through the optimization process. In scenarios "RE50WP0-CO2L/H", "RE50-WP50-CO2L/H" and "RE50-WP100-CO2L/H", solar and wind power production were constrained to satisfy 50% of the global electricity demand. Contribution share of wind power was varied from zero to 100% of the total solar and wind power production in 50% intervals. Scenarios and underlying assumptions are described in Table 1.

Table 1: Scenarios and underlying assumptions.

Scenario	Underlying Assumptions
Base-CO2H	- Limitation of total CO_2-emissions to 10069 million metric tons - New installations of solar and wind power are not allowed
Base-CO2L	- Limitation of total CO_2-emissions to 5745 million metric tons - New installations of solar and wind power are not allowed
REOPT- CO2H	- Limitation of total CO_2-emissions to 10069 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potential
REOPT-CO2L	- Limitation of total CO_2-emissions to 5745 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potential
RE50-WP0-CO2H	- Limitation of total CO_2-emissions to 10069 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potential - Solar and wind power are forced to satisfy 50% of the total annual electricity demand - Wind power contribution share is 0% of total solar and wind power production
RE50-WP50-CO2H	- Limitation of total CO_2-emissions to 10069 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potential - Solar and wind power are forced to satisfy 50% of the total annual electricity demand - Wind power contribution share is 50% of the total solar and wind power production

Table 1: Continued.

RE50-WP100-CO2H	- Limitation of total CO_2-emissions to 10069 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potential - Solar and wind power are forced to satisfy 50% of the total annual electricity demand - Wind power contribution share is 100% of the total solar and wind power production
RE50-WP0-CO2L	- Limitation of total CO_2-emissions to 5745 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potential - Solar and wind power are forced to satisfy 50% of the total annual electricity demand - Wind power contribution share is 0% of the total solar and wind power production
RE50-WP50-CO2L	- Limitation of total CO_2-emissions to 5745 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potential - Solar and wind power are forced to satisfy 50% of the total annual electricity demand - Wind power contribution share is 50% of the total solar and wind power production
RE50-WP100-CO2L	- Limitation of total CO_2-emissions to 5745 million metric tons - Upper capacity boundary for new installations of solar and wind power at each model region is the technical potent - Solar and wind power are forced to satisfy 50% of the total annual electricity demand - Wind power contribution share is 100% of the total solar and wind power production

Fig. 1 shows the produced power categorized by technology type along with the marginal price of CO_2 emissions for selected scenarios. A tighter CO_2 limit leads to a higher CO_2-price for comparable scenarios. It may be realized that the marginal price reduces with increased production of VRES. Furthermore, at the given penetration share of solar and wind power and a specified CO_2 emissions upper limit, the marginal price decreases with the contribution of wind power. In -CO2L scenarios, it reaches its lowest level in “RE50-WP100-CO2L”. This is also obtained in scenario “REOPT-CO2L”, in which the contribution share of solar and wind power is determined by the optimization. In this scenario, penetration share of wind power reaches 52% of total electricity demand.

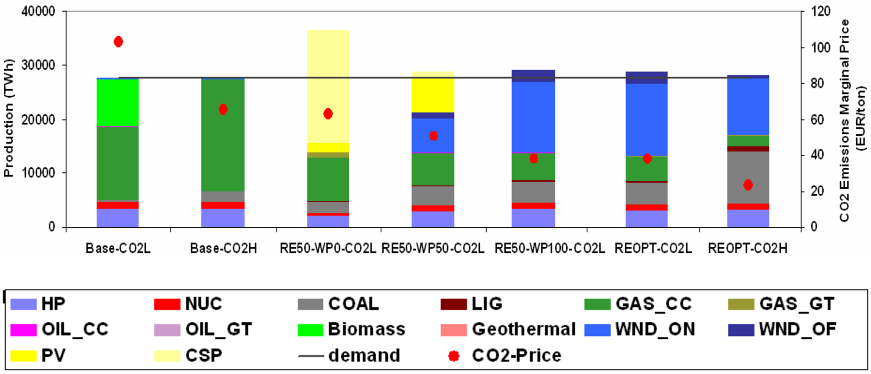

Figure 1: Total produced power categorized by technology type and CO_2 emissions marginal price for selected scenarios; year 2025.

3.2 Large-scale integration of VRES and the role of international exchange

Here, required investments in VRES to satisfy proposed emissions reduction targets, influence of international exchange, and development of the carbon price through a long-term period at different framework conditions are studied.

Optimization was performed through a time horizon from 2020 to 2040 with 5 5-year time steps. Extension of wind power and solar was determined by the optimization and limited due to the technical potential of each model region. It was assumed that nuclear and hydro power plants are not expandable beyond the existing levels. Installed capacities of storage up to the year 2009 were set as upper capacity boundaries. To analyze the influence of international exchange in an ideal globally-interconnected structure, results of the scenario "No-GE" without the possibility for grid extension were compared versus scenario "GOPT" that optimizes extension of cross-border interconnections. Table 2 gives a brief overview on the scenarios.

IPCC Working Group one (WG1) proposed the early-action scenario for 550 ppmv concentration level (IPCC [21] and Manne and Richels [22]). In a more stringent scenario (represented with the prefix "-CO2L"), CO_2 limits were tightened according to the category I of the stabilization scenarios in IPCC Assessment Report 4 [2]. The CO_2 emissions path was set to the minimum path in Nakicenovic [1], which leads to the stabilization of CO_2 only concentrations at the level of 350 ppmv by 2100. Total CO_2 emissions of the power sector in 2000 reached 9395 million metric tons [19], i.e. 42.2% of total CO_2 emissions [22]. Here, total CO_2 that may be emitted from the power sector at each time period was approximated based on the specified stabilization scenarios and contribution of the power sector. Implemented CO_2-limits are given in Table 3.

Total Optimized capacity mix is shown in fig.2. Total wind power capacity in "CO2H-GOPT" reaches 2822 GW by 2020 and rises to 10000 GW by 2040. Average wind power capacity factor is around 27%; penetration share of wind power reaches 58% of global electricity demand by 2040. In the more stringent

Table 2: Scenarios and underlying assumptions.

Scenario	Underlying Assumptions
GOPT-CO2L	- CO_2 abatement based on the category I of the stabilization scenarios in IPCC Assessment Report 4 - Grid extension is optimized
GOPT-CO2H	- CO_2 abatement based on the IPCC Working Group one (WG1) scenario - Grid extension is optimized
NoGE-CO2L	- CO_2 abatement based on the category I of the stabilization scenarios in IPCC Assessment Report 4 - Grid extension is not allowed
NoGE-CO2H	- CO_2 abatement based on the category I of the stabilization scenarios in IPCC Assessment Report 4 - Grid extension is not allowed

Table 3: Implemented CO_2 limits.

CO2 limit (Mio.ton)	CO2H	CO2L
2020	10059	6107
2025	10335	4698
2030	10611	3758
2035	10777	2819
2040	10943	2067

scenario “CO2L-GOPT”, wind power capacity rises from 4570 to 15285 GW. Having a lower CO_2 limit, coal-fired capacity is reduced while there is a higher installation of gas-fired plants compared to “CO2H-GOPT”. The influence of a global super-grid may be realized by comparing the scenario “-NoGE” with “-GOPT”. Fig. 2(b) and (d) clarify over-installation of capacities in “-NoGE”; more gas-fired plants and wind power parks have been installed to satisfy the same CO_2 limit as in fig. 2 (a) and (c).

Fig. 3 (a) and (b) show the total installed capacity of photovoltaic (PV) and concentrating solar power (CSP) systems corresponding to the optimized interzonal transport capacity at each time period in “-CO2L” scenarios, respectively. Solar systems at the considered costs and efficiency are not selected for large-scale penetration in scenarios that optimize grid extensions. However, in “CO2L-NoGE” scenario, corresponding to the lower level of the vertical axis in fig. 3 (a) and (b), total installed capacity of solar power systems shows a significant increase in the latest periods; it reaches 5 GW in 2035 and rises to 18 GW by 2040.

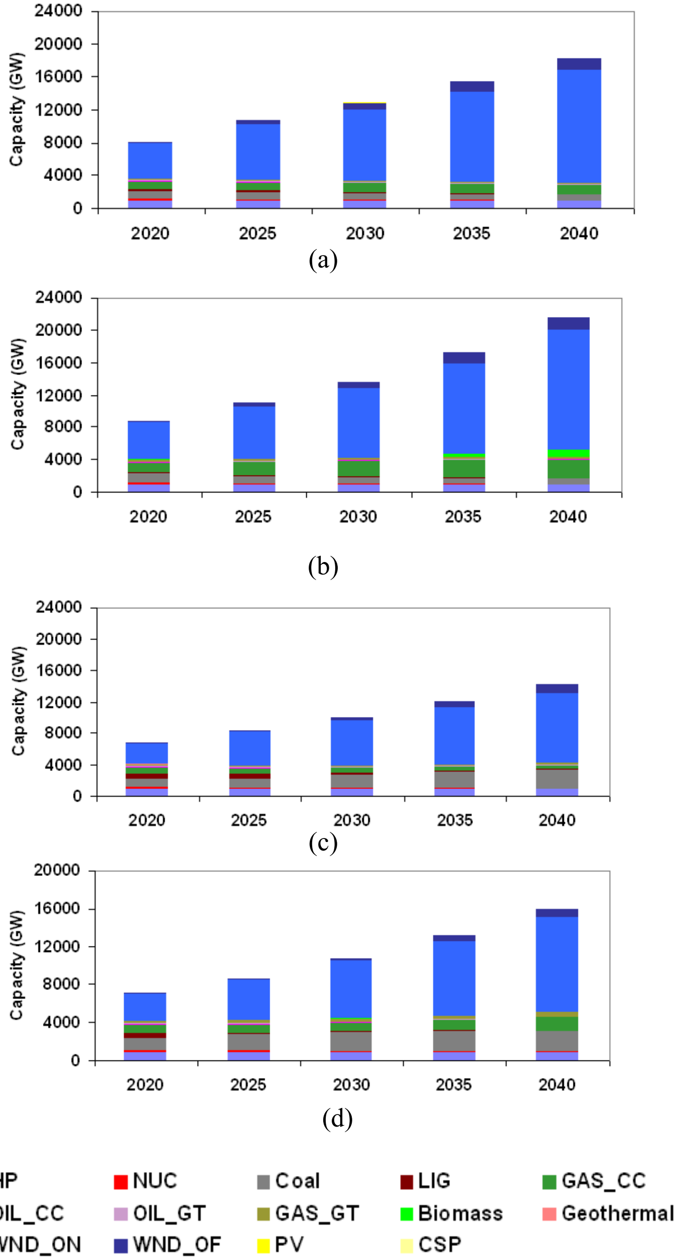

Figure 2: Optimized generation capacity mix 2020-2040 (a) Scenario CO2L-GOPT (b) Scenario CO2L-NoGE (c) Scenario CO2H-GOPT (d) Scenario CO2H-NoGE.

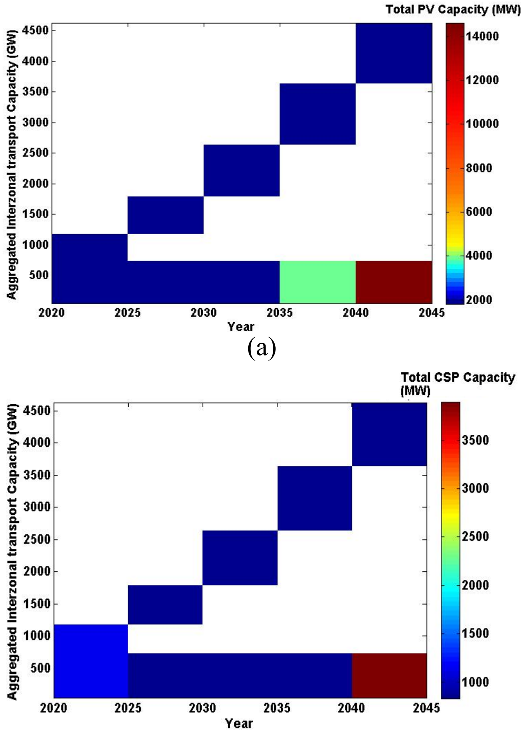

Figure 3: Optimized capacity of solar electric systems in 2020-2040 for -CO2L scenarios; (a) PV (b) CSP.

Fig. 4, for instance, shows the geographic distribution of transport capacities in 2035 resulted from the optimization in "-CO2L" scenario compared to "CO2H". Capacities of up to 206 and 343 GW are installed in "CO2H-GOPT" and "CO2L-GOPT", respectively, to transport the emission-free wind power from regions with a high level of technical potential to the high load centres.

The influence of a global super-grid may be realized by comparing scenario "-NoGE" with "-GOPT". In "CO2H-GOPT", certificate price does not show any significant increase through the time horizon and remains near 16 €/ton (fig. 5). However, in "CO2H-NoGE", it rises to 35 € /ton by 2040. This effect becomes much more significant with tightening the CO_2 limit; certificate price rises to 147 €/ton in "CO2L-NoGE" by 2040 compared to 61 €/ton in "CO2L-GOPT".

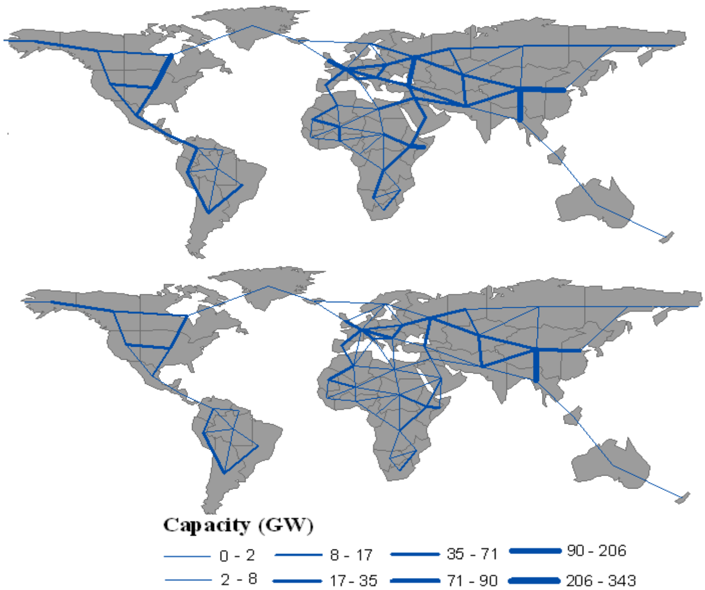

Figure 4: Optimized transport capacity in 2035 (a) scenario CO2L-GOPT (b). Scenario CO2H-GOPT.

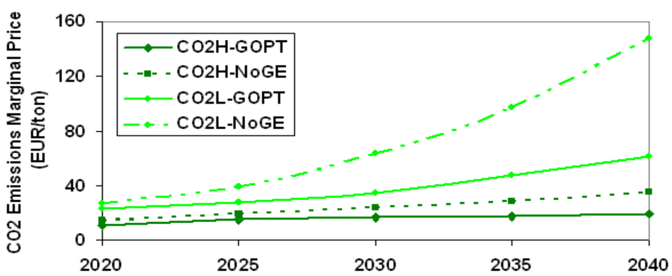

Figure 5: CO_2 emissions marginal price.

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