Influence of CO_2 taxation and hydrogen utilization on the cost-optimal development of the German power system by 2050

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Overview

The aim of this study is to determine the viability of emission regulations and various generation technologies in the German electricity supply system for the year 2050. The European carbon trading scheme, which attempted to cap emissions at a specific limit, is argued by many to be an insufficient measure; opening the discussion for a taxation of CO_2 by each emitter instead. In parallel, the possible role of hydrogen–both produced and imported–in the future electricity supply by their combustion in the combined cycle gas turbines (CCGT) plants will be investigated. In the course of the study, the cost-optimal way to reduce CO_2 emissions by up to 95% (compared to 1990) is examined, assuming various projections for electricity demand of 2050.

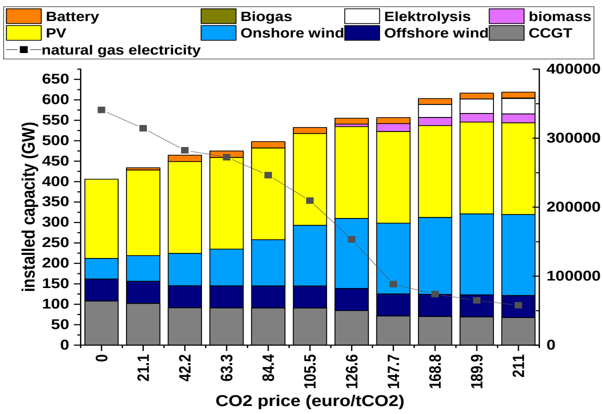
Methods

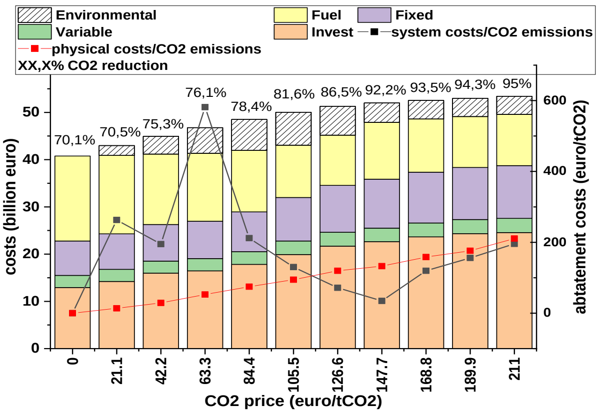
The system costs considered in this study consist of investment costs, fixed and variable costs of plant operation, fuel costs and the costs accounting to a potential CO_2 taxation. All costs are calculated on an annual basis; investment costs are converted to annual costs using the annuity method. The CO_2 costs include all CO_2 emissions from the natural gas-fired CCGT, which is the only allowed fossil-based generation mode in the model. For investigating the cost-optimal system dynamics, the following input variations were made: 1) choice of a CO_2 tax or a defined yearly CO_2 limit and 2) a scaling of the year-round hourly time series for electricity demand. The cost-optimal development of each system variant is achieved with the linear energy system modeling framework *urbs*. Here, the German energy system is modeled as a single-node (hence ignoring the grid constraints) and focuses only on the electricity sector. The work comes in two case studies: the *tax-instead-of-limit* and the *growing consumption*.

In the *tax-instead-of-limit* study, an equivalent CO_2 tax corresponding to a 95% decrease in emissions is calculated by accessing the dual variable of the CO_2 limitation constraint of the system model. Then, the constraint is removed from the model, and a CO_2 tax is introduced with a value from zero up to the 95%-reduction achieving amount. This way, the gradual effect of the tax instead of the limit, and the distribution of the system costs (between the physical costs and the tax-resultant share) is examined.

Growing consumption study: Studies argue that the German electricity demand by 2050 is highly uncertain as it largely depends on the electrification rate of heating and mobility. In order to investigate the generation technologies that are preferred by the model in a stepwise manner, the demand is linearly varied from the 2017 values until its doubling and the cost-optimal results are obtained under a CO_2 reduction target of 95%. Moreover, the utilization mode of hydrogen as a carbon-neutral flexibility option is investigated under various import prices.

Results





Figures 1 and 2. Results of the "tax-instead-of-limit" study.

Figures 1 and 2 illustrate the results of the *tax-instead-of-limit* study. Utilization of natural gas in CCGT continuously decreases with the growth of the CO_2 tax. This reduction is replaced between the CO_2 prices 21.1€/t and 105.5€/t by the build-up of PV, wind turbines and battery systems. Offshore wind turbines are highly favoured even without any CO2 tax, deployed up to their assumed potential limit of 54 GW. Solar plants reach their expansion potential (224 GW) at the CO_2 tax of 42.2€/t. After this point, a cost-optimal combination of onshore wind and remaining electricity sources is required. From a CO_2 tax of 126.6€/t the further reduction in the dispatchable capacity of CCGT is replaced by the expansion of biomass plants. From 168.8€/t upwards, electrolysis in combination with the further reduction of gas-based electricity could lead to cost savings. The installed capacity of CCGT remains the same despite its mode of operation gradually shifting to hydrogen-firing. Hydrothermal geothermal plants are never economically viable independent of the CO_2 tax. The installed capacity of CCGT will always remain high, even though the natural gas-based electricity generation decreases. The reason for this is the favorable investment and fixed costs as well as the better efficiency of CCGT plants compared to the other dispatchable power plants. As a result, their higher capacity can account for the largest variations in the demand.

Figure 2: Fuel costs decrease always due to the declining utilization of natural gas. Investment costs rise because of the expansion of PV, wind and battery systems until the CO_2 price grows to 105.5€/t. Up to this point, a very minimal increase in the physical costs (total system costs minus CO_2 tax payments) takes place, as the increase in the investment is compensated by the strong reduction in the fuel costs. So assuming that the CO_2 payments are redistributed socially, the economic burden is negligible even with a carbon price of 84.4€/t. After this point, expansion of biomass plants and electrolysers contributes to higher investment and fixed costs and increases the physical system costs significantly. The absolute CO_2 tax payments grow until the 105.5€/t mark, although the natural gas-based generation is declining. From this point onwards, these payments show a falling trend.

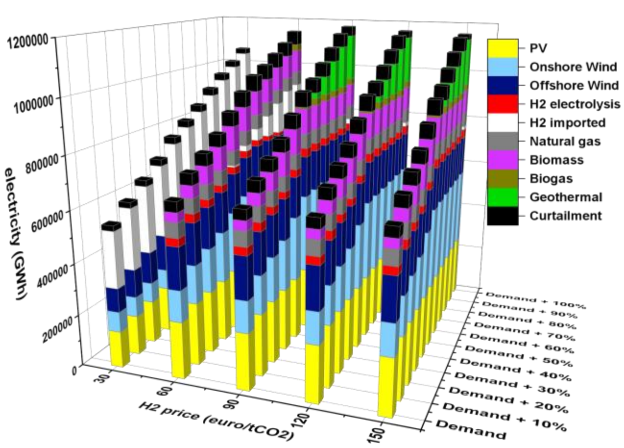


Figure 3. Electricity balance vs. variation of demand and H_2 import price, CO_2 limit 95% (no tax).

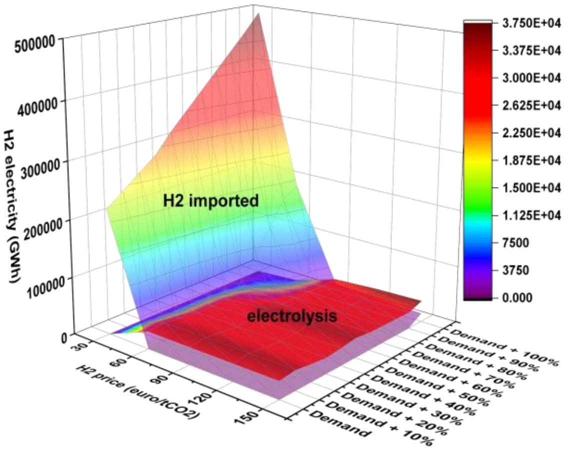


Figure 4. Electrolysis vs H_2 import with variation of demand and H_2 price, CO2 limit 95% (no tax).

Figures 1 and 2 illustrate the results of the growing consumption study. The extremely favourable H2 price of 30€/MWh leads to complete non-use of natural gas, as using H_2 instead in CCGT's for backup production becomes slightly cheaper even without any carbon price. Electricity generation from imported hydrogen as well as from PV and wind turbines is increasing in line with the rise in demand. Offshore wind and PV show a higher construction speed than onshore wind due to better economic efficiency. *H_2 price of 60€/MWh:* the natural gas usage is restricted at the value (57,000 GWh) defined by the 95% CO_2 limit. So the system should strive for CO_2-free alternatives in order to cover the demand. Integration of the renewable surpluses through electrolysis serves to increase flexibility and avoid additional expansion costs (as low-cost PV systems are supported). In parallel, biomass power plants are utilized as the backup capacity of the system (already for today's demand levels). But as the biomass potential is fully exploited by the 40% demand increase scenario, the H_2 imports start to take place. So for the system, it is more worthwhile to import hydrogen instead of integrating the entire renewable surpluses or investing in other local renewables (biogas and geothermal). The H_2 import with prices higher than 60€/MWh occurs only in the doubling of consumption as the potential of biogas and geothermal are fully exploited. At this point: the more the H_2 price rises, the lower is the electricity supply from imported H_2 and the higher from produced H_2. For H_2 prices over 30€/MWh a higher electricity production takes place for each consumption case. This is related to the efficiency of storage and electrolysis systems, which requires an increased total current output from the renewable systems.

Conclusion

The study demonstrates that a CO_2 reduction target of up to 82% can be achieved cost-effectively through the extension of PV, wind and battery systems. A cost-optimal reduction of CO_2 emissions between 82% and 95% requires the deployment of biomass and electrolysis. The production of H_2 by electrolyzers is, for reasonable H_2 prices, cheaper than the import of hydrogen. Nevertheless, the import of carbon-neutral hydrogen can cover any increase in electricity demand. The integration of the surpluses through battery storage and electrolyzers aims to save costs by increasing the expansion of low-cost photovoltaic systems and at the same time limiting the expansion of expensive generation technologies.