

Sustainable Energy Development under Uncertainty

Electricity generation is with 40% the most important source of CO₂ emissions. At the same time, climate science has established that anthropogenic greenhouse gases contribute to an acceleration of global warming with adverse effects such as sea level rise and desertification. Given that many OECD countries have to replace substantial portions of their electricity-generating capacity over the next 10-20 years, investment decisions today will determine the CO₂-intensity of the future energy mix. It is thus important to understand how investment decisions are made in the electricity sector and how they can be effectively influenced by policy.

Investment in the electricity sector is characterized by irreversibility due to the large up-front sunk costs typical for power plant installation. Next to this, there are different sources of uncertainty having an impact on investment decisions such as the volatility of fossil fuels, uncertainty about pace and direction of technological developments, and uncertainty about future policy and regulations. The flexibility to postpone or bring forward investments in the light of these uncertainties makes real options theory a valuable modeling approach to investigate the effect of different types of uncertainty on investor behavior.

In contrast to the claim of many stakeholders in industry that the fluctuations in the price of CO₂-permits will lead to a postponement of investment into less CO₂-intensive generation technologies, the results of this thesis show that such market uncertainty can be interpreted as a lack of perfect information and that optimizing under incomplete information will lead to an earlier transition to CO₂-saving technologies. The uncertainty due to the vagueness of policy aims, on the other hand, leads to a substantial increase in the option value, i.e. waiting becomes more valuable than exercising the investment option and a transition to clean technologies is slowed down significantly.

The uncertainty associated with the technological progress of renewable energy technologies leads to a postponement of investment in a real options model, where technical change follows a Poisson process. The reason for this is that the option value is high if large leaps in productivity improvement or strong cost reductions can be expected. Even the simultaneous inclusion of stochastic fossil fuel prices in the same model does

not make renewable energy competitive compared to fossil-fuel-fired technology -- based on the data used -- for the short and medium run. This implies that policy makers have to step in if renewable energy is supposed to get diffused more quickly, for example through penalties on the combustion of fossil fuels or subsidies to renewable energy technology deployment. Otherwise, old fossil-fuel-fired equipment will be refurbished or replaced by fossil-fuel-fired capacity again, which enforces the lock-in of the current system into unsustainable electricity generation.

The vintage-portfolio model developed in this thesis offers a somewhat more optimistic outlook on the future by taking into account the effect that diversification can have on the energy mix in the future. While it is true that e.g. UK emissions reductions policies like permit trading and renewables quotas come at an extra cost to investors and thus ultimately also to consumers, the generating portfolio's cost variance will be much lower, which must be valued positively. Since the focus is on the cost-side of the planning problem and problems of safety and waste disposal are largely ignored, nuclear energy is found to offer an alternative possibility to bridge the gap between the current energy system, which is largely based on fossil fuels, and the diffusion of less CO₂-intensive generation capacity in the future.

Methodologically, the new vintage-portfolio framework delivers results about the effect of technological uncertainty, which differ from the typical results generally found in real options and optimum portfolio theory. In the face of larger technological certainty, investments are temporarily postponed and the investment in the substitute technologies increased, while larger uncertainty in fuel prices, for instance, always leads to less investment in all the three models. All of them thus find a negative relationship between investment and uncertainty in the beginning of the planning period, which can be attributed to the fact that technical change is embodied in the latest vintages of a technology. It is therefore optimal to wait and invest into new vintages that have in the meantime benefited from the technical change that occurred with more certainty. Intertemporal optimization in combination with the cumulative character of technical change thus generates results that are consistent with the creation of an option value in the vintage portfolio model.