An Agent Based Model of the System of Electricity Production Systems: Exploring the Impact of CO_2 Emission-Trading

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Abstract - *To elucidate the impact of CO_2 Emission-Trading on the European electricity production system-of-systems an Agent Based Model has been developed. The model emulates the long-term evolution of the European electricity production system-of-systems as a series of investment decisions by independent agents. Simulation results are reported that underpin recommendations for European CO_2-policy. A live model will be presented.*

Keywords: Agent Based Model, Emission-Trading, Power Production.

1 Introduction

Power grids for electricity connect electricity producers and consumers. In the 20th century, around the world, electricity infrastructure has become a critical backbone of modern industrial society. In Europe, re-regulation, liberalization and privatization of this sector is underway. As a consequence, in the past two decades the spectrum of actors that operate and shape this system-of-systems (SoS) has dramatically diversified. In many countries a wholly state-owned and government-controlled vertically integrated company operated and maintained electricity production, transport and distribution. Presently, a mix of major stock market-listed energy companies, state-owned but privatized companies and government-controlled network operators deal with production, transport or distribution. In addition a range of new actors has entered the scene, e.g. regulators, the power exchange market, power brokers, retailers etc..

As shown in Figure 1, today's electricity infrastructure is an assemblage of technical systems and a social network. Technical facilities for power generation, the grid and power consuming equipment are used and manipulated by actors that invest in, operate and/or control these facilities. This true system-of-systems operates in a geopolitical setting, a market economy but also in a natural environment, which acts as source for fossil fuels and oxygen and a sink for large quantities of carbon dioxide (CO_2).

The cost of facilities and fossil fuels is determined in the market economy. CO_2 emission, however, always has been unconstrained and free-of-charge. As of January 1st 2005, in the European Union, however, CO_2 emission trading (CET) is putting a price on CO_2 emissions. The EU's intent is to drive down CO_2 emissions using the market's "invisible hand" [1].

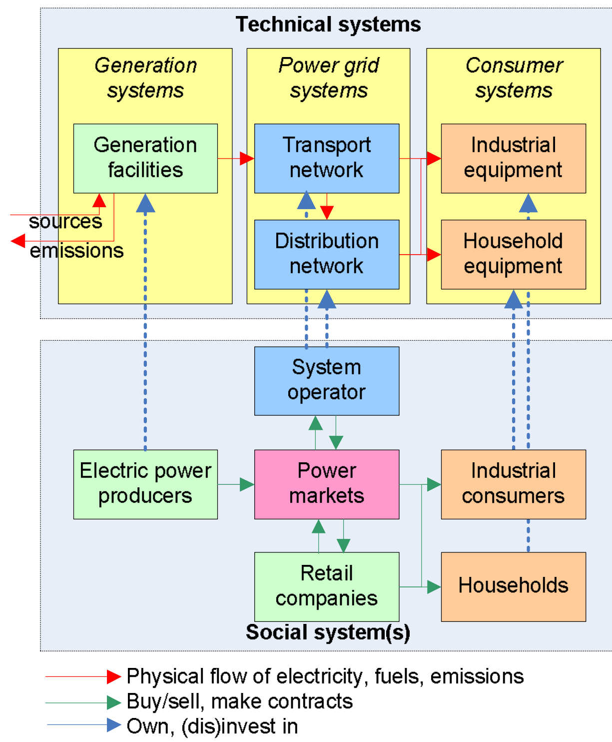

Figure 1. The electricity infrastructure as a systems-of-systems

1.1 Problem definition

The central question addressed in this paper is *"how does carbon dioxide emission trading (CET) impact the European system-of-electricity-production-systems (SoEPS)"*.

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1.2 Overview

Our goal is to provide scientifically underpinned analysis rooted in sound representation of the technology, system structure and actor behavior involved in SoEPS. Since this SoS is shaped by decision by a variety of actors, we elected to develop an Agent Based Model (ABM) to emulate the SoS evolution over a period of 75 years. Relevant developments in the system's external world were captured in environment scenarios, following Enserink *et. al*, [2].

2 Background and conjecture

To achieve reductions of carbon dioxide (CO_2) emissions as stipulated by the Kyoto Protocol, carbon dioxide emission trading (CET) is setup in the EU as of January 1st, 2005 (*EU Directive 2003/87/EC*). The major argument given to introduce this policy is that "the invisible hand" would lead to emission reduction at the lowest cost [3]. Since electricity production accounts for one third of CO_2 emissions in Europe, this SoS is one of the main sectors to which CET applies. [4] In the short term, CET is expected to reduce CO_2 emission by stipulating increased operational efficiency. In the long term, CET may lead to emission reductions by influencing the outcome of investment decisions on power generation capacity. In the liberalized electricity production sector, however, to elucidate the overall response of the system of electricity production systems to CET is not straightforward, because CO_2 emissions are the result of disaggregate investment decisions by individual electric power producers – the system's response emerges.

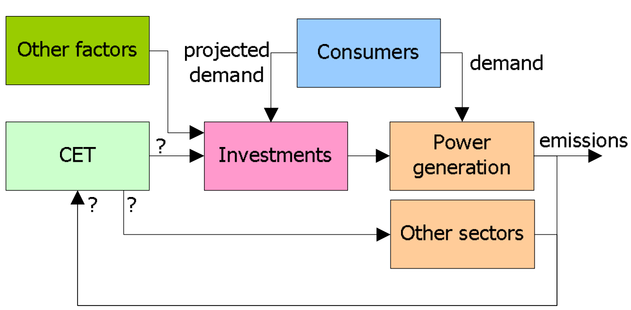

Figure 2. The impact of CET on emissions by power generation is not straightforward

In the EU, electricity production is separated from transport, distribution and retail. Governments in the EU created markets for electricity production to increase the efficiency and reduce costs of electricity production. This allowed us to limit the agent-based model (ABM) to the SoEPS.

Investment decisions on electricity production capacity by any actor are strategic decisions that are affected by interrelated capital markets, fuel markets, electricity markets and the portfolio of acceptable and available generation technologies. The stakes are high, as investments range from 100 M€ to 2000 M€ per facility, uncertainty is endemic – how will markets develop, what will competitors do etc. These decisions are driven by expectations – fuel prices, electricity supply-demand balance etc.

Amidst these market forces it remains to be seen whether CET will exercise a decisive influence on technology selection. Electricity production is not a system with a "perfect market". An oligopoly is in place that may lead to market imperfections through strategic behavior of individual players. Next, information is asymmetric to the different parties. In addition, since lifetime of power plants is measured in decades, change in the electricity generation portfolio is bound to path dependence.

Whilst the precise effect of CET is uncertain, we conjecture a suitable ABM will yield valid patterns and ranges of the SoS response to the introduction of CET.

3 Model development

An agent-based simulation model may be defined as "a collection of heterogeneous, intelligent, and interacting agents, which operate and exist in an environment, which in turn is made up of agents" [5, 6]. An ABM thus is a set of interacting *'agents'* with certain properties.

The use of ABM is well defined by SAM Corporate Sustainability Assessment [7]: "Agent-based models are used to address dynamic systems. These models emphasize modeling behavior at the lowest practical level, with an interest in studying the emergence of spatial arrangements and agent interactions, as well as the evolution of strategies for agent interaction with the environment and other agents [...]. Agent-based models are well suited to model strategies of different stakeholders, their interactions and the outcome of such interactions."

The main component of ABM's is the agent. Which properties an entity has to feature in order to deserve to be called an agent is not clear-cut: agent definitions range from a mere subroutine to a conscious entity [7-10]. An overview of the properties of agents found in literature is given by Schieritz and Milling [9].

According to Jennings "An agent is an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives" [8]. An agent thus is a piece of software code in a computer that describes its goals and the ability of taking specific actions. The agents in the model described in this paper have four components, following Weiss [11] and Bussmann *et al.* [12]. First, agents have a set of goals, defining the objectives the agent *wants* to accomplish. Second, the working memory of agents entails information about itself, in other words, the agents' *state*. Next, the social memory is a set of knowledge on the behavior of the agent and other agents. Finally, social engagement rules define the behavior of an agent. It contains the abilities an agent has to interact with others or make decisions.

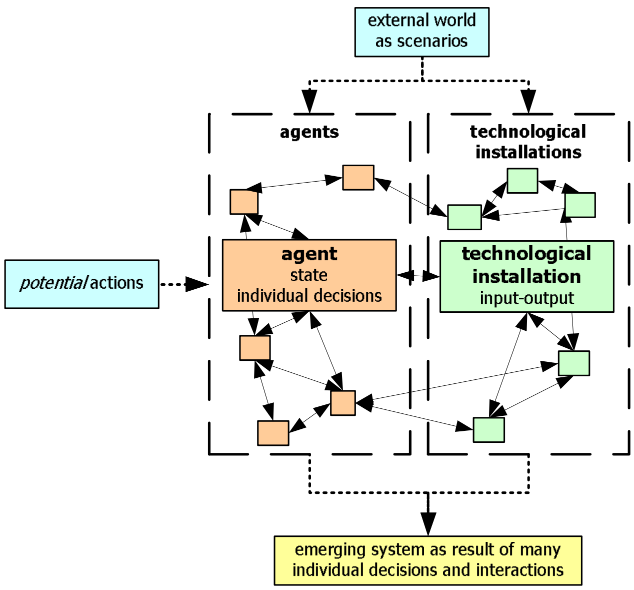

Figure 3. Agents in an agent-based model decide on their actions.

A preliminary specification of an agent-based model is presented of the long-term aggregate impact of CET on CO_2 emission via disaggregate investment decisions by individual electric power producers. An overview of the model components is given in Figure 3.

The model is defined by the sequence of potential operational and strategic actions of agents, by exogenous trends modeled in scenarios and by the definitions of agents' style and behavior and by the portfolio of available technologies and installed facilities. A major characteristic of an agent-based model is that agents autonomously decide whether or not to undertake specific actions. Thus, in our model agents that possess and control electricity production facilities decide autonomously on investment or disinvestment and on the bids they put out to sell the electricity they produce They arrive at these decisions using available information and applying hard criteria, such as the profitability of their options. Also softer factors, such as nuclear fear and environmentally friendliness may enter the equation. Each agent may apply a unique weighing of the information and apply these criteria in a different manner. The result is an explicit model of the disaggregate decision-making that shapes the complex interrelated system of electricity production systems.

Important parts of the market economy - the fossil fuel markets and the markets for generation technologies - are modeled as a range of possible futures – a set of exogenous variable that evolve in specific scenarios. In the specification of this first version of the agent-based model electricity demand is also modeled as an exogenous variable, second-order effects of CET, such as technological innovation are assumed to be absent. The number of electric power producing players is constant as well as their beliefs and style.

The evolution of the Dutch electricity generation portfolio is simulated, under the influence of these exogenous scenarios. Since the model is developed using a modular setup, CET, one of the modules, can be switched on or off to test the impact of CET.

4 Model implementation and results

The model has been implemented using the ABM framework developed by Nikolic et al [13, 14]. The shared ontology – a formalized structure of concepts with a knowledge base – therein built in Protégé [15] was used to define the power companies as agents, their power producing facilities and the available technologies. The source code for the model was written in the integrated development environment, Eclipse [16]. In addition, Repast was used as agent-based simulation tool [17].

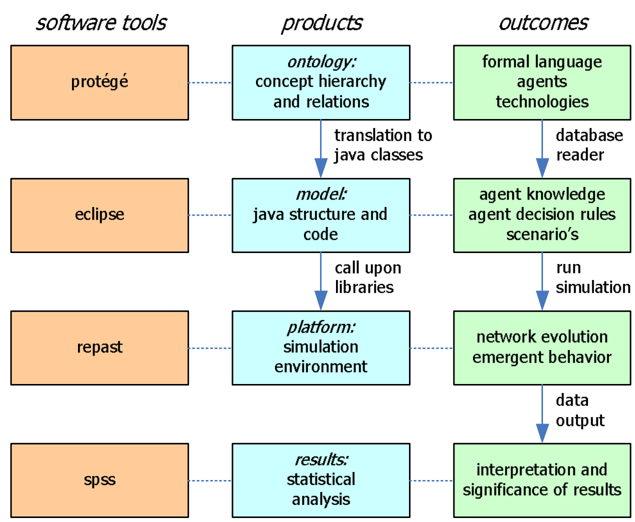

Figure 4. Software tools in the ABM simulation engine framework

In order to obtain a robust image of CET-impact parameter sweeps over the entire scenario and parameter space were completed by running some 450 simulations. The results obtained were statistically analyzed by using SPSS. In the analyses, no values of single runs were used, but average values over the scenario and parameter space. In Figure 4 an overview of the software tools in the ABM simulation engine framework is given.

Based on this preliminary agent-based model, it is found that CET leads to large reductions in actual CO_2 emissions in all scenarios (see Figure 5). The results also show, however, that only in a few scenarios the emission reduction is adequate to meet the Kyoto target. In most scenarios it appears that CO_2 emission exceed the current cap applicable for electricity generation in the Netherlands. If this is indicative for the development in other sectors as well it is not likely that the Dutch Kyoto target will be met.

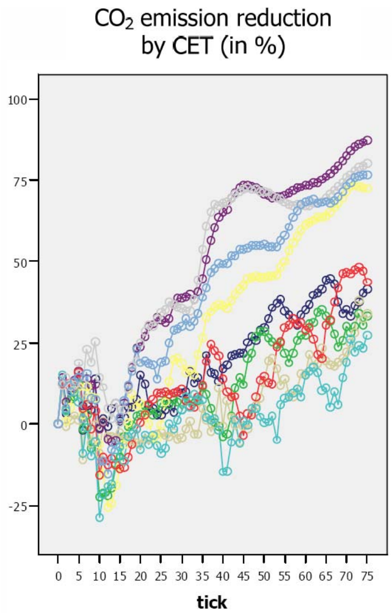

Figure 5. Emission reduction potential of CET in different scenarios

As expected intuitively, emissions are reduced by a shift in the electricity generation portfolio towards less CO_2 intensive power plants. in the simulated scenarios, however, a significant electricity generation portfolio shift only occurs after three decades (see Figure 6). Since a significant growth in electricity demand is to be expected and because of the developments in fossil fuel prices, an absolute increase in CO_2 emissions might occur in the coming decades, even with CET implemented due to a dramatic shift towards relatively low-cost but CO_2 intensive coal.

CET leads to an increase in electricity prices, as was expected and a redistribution of financial means from consumers to producers of electricity was noted. Surprisingly, it was found that CET slows down the speeds of shifts in the electricity generation portfolio, because the price signals it generates are too weak.

The simulation runs where CET is active appear to justify the conclusion that the effectiveness of CET in reducing emissions relies on a decrease in electricity demand, technological innovation and fuel prices. However, these are largely CET-independent factors. CET decreases electricity demand only by a possible increase in electricity price. As stated, technological innovation is not included in the model. Finally, fossil fuel price is exogenous. It may be seen that world-scale evolution of fossil fuel prices are not influenced directly by CET but only via its impact on the electricity generation portfolio.

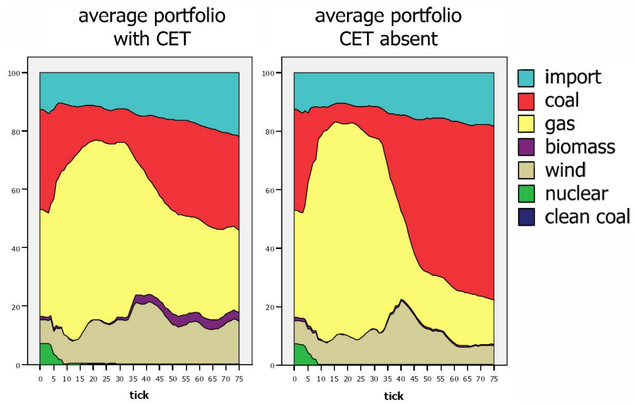

Figure 6. Average development in the E-portfolio distribution

5 Conclusions, recommendations and outlook

CO_2 emission trading (CET) is implemented as s policy instrument to reduce CO_2 emissions at the lowest cost. In the decentralized System of Electricity Production Systems (SoEPS) in the Netherlands, with players forming an oligopoly, the effect of CET has to be achieved by an impact on the technology selected when investing in new or replacement generation capacity.

In the agent-based simulations the impact of CET is relatively small and requires a long time to materialize. Technological innovation, however, to improve operational efficiency was not included. One may argue, however, that the effect of CET thereon maybe limited, because of the long-history of incremental innovation and efficiency gains realized in the Dutch electricity sector as a result of market and regulatory pressure and energy covenants agreed upon.

On the basis of the simulation results some recommendations can be given: the EU and member state governments must reduce the cap to accelerate the portfolio shift. This will prevent new CO_2 intensive capacity to be built and will accelerate the replacement of such facilities with CO_2 extensive generation. Secondly, only a sufficiently strong and consistent price-signal will decrease the uncertainty of strategic long-term investment decisions of electric power producers. Third, uncertainty in policy and regulation for the entire expected economic lifetime of power plants to be built should be minimized. Finally, research and innovation must be stimulated in order to develop new solutions for reducing CO_2 emissions, and innovative institutional and regulatory arrangements must be adopted in order to provide more incentives and possibilities to connect small and medium size generation to the grid and to stimulate consumers to decrease their electricity demand.

The first model demonstrated the feasibility and suitability of ABM modeling to explore the evolution of the SoEPS. Since the model and the framework are modular, the model can and will be extended to capture decisions that affect both short- and long-term performance.

The main extensions to be expected are the integration of ABM with the research fields of game theory and system dynamics, the implementation of technological innovation by electric power producers, the inclusion of advanced investment decision rules based on discounted cash flow, real options and decision-making under uncertainty. The span of the model can be increased by the development of a simulation model of the entire EU system. Finally, additional validation techniques must be developed as well as a fully equipped agent-based simulation engine, which allows one to build, maintain and extend these models in a user-friendly manner.

We believe that with these extensions Agent-based modeling can contribute dramatically to the understanding of the dynamics, stability and the management of Systems of Systems.

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