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Institutional adaptation to cooling water scarcity for thermoelectric power generation under global warming

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ABSTRACT

This article studies adaptation of institutional arrangements for water regulation to climate change. Power plants occasionally need to curtail production during heat waves, causing economic losses and putting power quality at risk. To avoid exacerbation of this problem due to climate change, the regulation of heat emissions from power plants may require adaptation. The analysis abstracts a mathematical model from a case study of the German Rhine catchment. The model compares three options for regulation with an analysis of transaction costs, and balances them with costs from environmental externalities. First, long-term and site-specific temperature caps lead to the comparatively lowest sum of social transaction and production costs if heat waves only increase in intensity. Second, a dynamic heat load plan performs better if heat waves only increase in frequency. Third, if both intensity and frequency of heat waves increase substantially, a specific contract between the environmental regulator and electricity producers (the minimum power plant concept) performs comparatively best. The article highlights economies of scale in transaction costs, and shows how institutional adaptation can depend on the speed of climate change.

1. Introduction

Heat waves can lead to substantial curtailment of production by thermoelectric power plants. This happened, for example, during the extremely hot summers of 2003 and 2006 in central Europe (Rebetez et al., 2008; Strauch, 2011), and led to electricity price spikes. Electricity utilities warned of the risk of a blackout. This is a serious problem for many electricity systems across the world (e.g. in the US, EU, China and Australia; Spang et al., 2014). At its root is the fact that thermoelectric power plants emit waste heat, in accordance with the laws of thermodynamics, usually to a water body. However, power plant heat emissions and water withdrawal are typically limited by environmental regulation (e.g. Macknick et al., 2012; Commonwealth of Australia, 2012; Xu et al., 2013), put in place to maintain the water quality and temperature of aquatic ecosystems (Frijters and Leentvaar, 2003). Adherence to such regulations can require partial or complete curtailment of production by thermoelectric power plants. There is thus a resource use conflict between electricity security of supply and the protection of river ecosystems.

Cooling water management is of high economic and societal relevance, because it is tied to the provision of electricity, an essential factor of production. In a changing climate, this conflict is likely to become more acute. Institutional adaptation of cooling water management to changing climatic conditions can already be observed and provides initial empirical evidence that can be used to assess alternative approaches. Which institutional adaptations can address increasing cooling water scarcity? More generally, how can institutions be designed to respond to long-term environmental change? This article addresses these questions by comparing alternative options for cooling water regulation in the electricity sector under anticipated climate change.

The article develops a general model of institutional adaptation to cooling water scarcity, using the German Rhine catchment as a case study to start from. It compares three institutional arrangements for cooling water regulation under different qualitative climate scenarios. By institutions, I understand "the humanly devised constraints that shape human interaction" (North, 1990), e.g. contracts, laws and organizational structures. Institutions are distinguished from organizations, e.g. governments, firms or water commissions, although the two are often closely related. Organizations are collective actors, while institutions are the constraints or rules that characterize them. This is a common definition in institutional economics. The article aims to contribute to institutional ecological economics (Paavola and Adger, 2005) by comparing the sum of transaction costs and social production costs between second-best institutional arrangements, and by investigating institutional change in response to exogeneous changes that alter cost and benefit structures (cf. Kingston and Caballero, 2009). The analysis employs mathematical techniques from the literature on qualitative reasoning (cf. Kuipers, 1994; Eisenack et al., 2007).

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Specifically, I analyze 'temperature caps', the arrangement in place in Germany prior to 2003; the 'minimum power plant concept', an arrangement that was developed in Germany following the 2003 heat wave; and the 'dynamic heat load plan', a feasible alternative approach that has, however, not been applied to date. The model shows how the comparative cost advantages of the arrangements depend on the frequency and intensity of heat waves, and on the speed of climate change. In the absence of climate change, the model shows that temperature caps perform best. This remains the case when heat waves become more intense but not more frequent. When heat waves become more frequent, the other institutional arrangements are less costly, despite higher transaction costs. The introduction of the minimum power plant concept after the 2003 heat wave in Germany conforms to the results of the general model. This has created a path dependency, which makes it unlikely that other arrangements will be adopted in the foreseeable future.

To my knowledge, this article presents the first institutional analysis of the cooling water issue. Existing studies on cooling water scarcity mostly estimate its quantitative effects (see Mideksa and Kallbekken, 2010 for a review). For the US and Europe, van Vliet et al. (2012) project increasing curtailment of power production under climate change. Several studies quantify the cost of curtailment of production by thermoelectric power plants (Koch and Vögele, 2009; Förster and Lilliestam, 2010; Linnerud et al., 2011; Rübbelke and Vögele, 2011; Golombek et al., 2012; Pechan and Eisenack, 2014), while others assess technological options (e.g. Feeley et al., 2008). Although some models explicitly represent water management plans (Koch et al., 2012), alternative options for regulating cooling water scarcity beyond the power plant level have been explicitly analyzed, to my knowledge, only for Texas (Stillwell et al., 2011), and the Rhine (Eisenack and Stecker, 2012), but not from an institutional economics perspective.

The present article provides concrete suggestions for how to adapt cooling water management to climate change, and provides the first scientific analysis of the minimum power plant concept as an institutional arrangement. It thus contributes to the still young field of the (institutional) economics of adaptation to climate change. Recently, the more general contribution of institutional economics to the analysis of adaptation to climate change has been explored (Oberlack, 2016; Gawel et al., 2012; Tompkins and Eakin, 2012). Although there is some work on adaptive institutions, few publications explicitly consider adaptation to climate change (exceptions are Adger, 2000; Doelle et al., 2012; Libecap, 2011 which analyze local environmental risks, forest management, and water resources, respectively). In contrast to the present article, these studies focus more on substractive resource use or do not consider changing environmental conditions. Roggero (2015) takes a more dynamic view on adaptation by local administration. Earlier work by Liebcap (1978) or Alston et al. (1996), for example, analyzes how new institutions are established or changed, in particular property rights, without referring to climate change. Likewise, several studies investigate changing water or waste management institutions without considering climate change or cooling water (e.g. Paavola, 2002, 2010; Levänen, 2015). Generally, there seems to be little work that investigates how long-term environmental change shapes institutions (but see Libecap, 2007). The present article shows in detail how both the level and the pace of climate change can determine the relative costs of different options for institutional adaptation.

Section 2 recalls the bio-physical basis of the cooling water issue, and Section 3 introduces the German Rhine catchment case study. Section 4 develops the general model and analyzes the three institutional arrangements in detail. Section 5 derives the results of the model. It assesses whether they fit to the case study, explores implications for future institutional change, and discusses the results. The concluding sections summarizes, while Appendix A contains the specification of the mathematical model and the proof.

2. General Bio-physical Basis

Before turning to the case study, this section outlines the general bio-physical basis of the role of cooling water in power generation (see, e.g., Frijters and Leentvaar, 2003; Feeley et al., 2008; Koch and Vögele, 2009; Förster and Lilliestam, 2010, for more detailed introductions). A thermoelectric power plant (e.g. powered by coal or uranium) converts primary energy into electricity with a thermal efficiency between 30% and 40% (up to 45% for modern plants, and up to 60% for combined-cycle gas turbines, IEA, 2012; Carapellucci and Giordano, 2013). The remaining energy is mostly converted to waste heat. The physical maximum thermal efficiency is expressed by Carnot's theorem and is lower if the temperature of the cooling medium (mostly water) is higher. Heat emissions are typically released to the environment, i.e. to the air or a nearby water body, very often a river.

The thermal efficiency further depends on the cooling technology. Technologies differ by the amount of water withdrawn, the amount of water consumed, and the amount of energy released into the water body. Only part of the withdrawn water is heated up and discharged back into the river; the remainder is consumed (e.g. through evaporation in a cooling tower). Technologies also differ in terms of their costs, with those that emit more heat into the river being cheaper. If there is temporarily not enough river water to take up the heat emissions, some power plants can shift to an alternative cooling technology; otherwise they need to curtail production to avoid overheating. Cooling water can be an essential production factor for electricity generation.

The effect on the water body depends on the amount of heat emitted, water consumed, and on the hydrological conditions. If heat is discharged into a faster flowing river the river temperature increases less. Hydrological conditions typically depend on the climate, weather and season, additional environmental factors, and upstream water use. Heat emissions have a variety of effects on water quality. These, in turn, can have secondary economic impacts. For example, the mortality of fish can increase considerably, and the costs of producing high quality drinking water rise.

A note on the use of the term *cooling water scarcity* in this article is in order here. Cooling water becomes scarcer if the river flow rate decreases, but also if the river water already warms up due to some causes. In both cases, the cooling potential of available water is reduced. The term thus denotes the joint effect.

The adverse effects of heat emissions do not only occur in the vicinity of the power plant. The increased water temperature can be measurable tens or even hundreds kilometers downstream (Lange, 2009; Stewart et al., 2013). Thus, ecosystems and other water users, including other thermoelectric power plants further downstream, are also negatively affected.

Due to climate change, hydrological conditions can be expected to change over the coming decades (van Vliet et al., 2011). The global average surface temperature is expected to rise by 0.3–4.8°C during the 21st century, and this will cause water temperatures to rise (IPCC, 2013). Precipitation patterns will also change. Overall, it is very likely that cooling water supply will become more scarce in the future.

3. Case Study from Germany

3.1. Data Sources

The following description is based on multiple data sources. Geographical, economic and institutional information was retrieved from public documents, research projects (e.g. Greis, 2007; Koch and Vögele, 2009; Förster and Lilliestam, 2010; Rothstein and Parey, 2011), official reports of the International Commission for the Protection of the Rhine (e.g. ICPR, 2009), and an environmental NGO (Lange, 2009). Legal documents were consulted (in particular the EU Freshwater Fish Directive, 78/659/EEC), as well as development approval documents for 34 power plant blocks (out of about 120 blocks with more