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A prospective analysis of waste heat management at power plants and water conservation issues using a global TIMES model

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ABSTRACT

In this study, to consider both water and electricity uses, we added water footprints related to the power system (cooling systems, gasification and flue gas desulfurization processes), to the global TIAM-FR prospective energy system model. With this modification, the TIAM-FR model can be used to ascertain whether future energy mixes might be plausible in terms of water availability. A number of scenarios were evaluated involving diverse policies concerning water or carbon emissions. We observed that the choice of cooling system and the use of carbon capture when considering policies on climate may significantly increase overall freshwater consumption. In regions where water is already scarce or is likely to become so, an increase in freshwater consumption levels or withdrawals may not be sustainable for the energy system. However, by incorporating water directly into the TIAM-FR model we can consider this resource as a constraint and evaluate the impact of water scarcity on electricity production in regions such as the Middle East.

1. Introduction

Numerous everyday appliances, such as lighting systems, air conditioning, domestic electric appliances, computers and multiple devices in all economic sectors rely on access to a continuous and secure source of electricity with few alternatives. Triggered by population growth and improved living conditions, the global demand for electricity increased sharply by 78% between 1990 and 2010 [1]. Hence electricity is recognized has a vital form of energy for both domestic and economic activities in today's modern societies. The intuitive relationship between electricity consumption and GDP growth has been investigated in analysis such as [2], which reveals a complex causal relationship depending on country income groups. Yet, along with the growing role of electricity and its links to observed economic growth, the world's thirst for electricity has also produced several identified environmental downsides: local and global environmental impacts, security concerns and water resources use. Thanks to constant innovation and research efforts, technical solutions have been proposed for each of these issues but their interplay remains complex. Coal or gas thermal power plants equipped with CCS (carbon capture and storage) and nuclear power are candidate solutions to mitigate the power sector's contribution to climate change, but they raise water and security concerns. Wind and solar power are alternative renewable candidates but raise reliability concerns for high penetration rates due to their intermittent nature and concentrated solar power plants also raise water issues. Although biomass can provide a renewable source of power with no intermittency issues, it has a significant impact on land use [3]. Below we briefly review previous analyses.

Due to the global nature of climate change, GHG (greenhouse gas) emissions quickly emerged as the main environmental concern. Emissions from power plants are directly related to the carbon content of their input fuels. With its 40% share of coal plants and growing demand, the power sector is the first and fastest growing contributor to energy-related GHG emissions [4]. Power-sector-related CO_2 emissions increased by 80% between 1990 which is the reference year for the Kyoto protocol and 2011 [5]. However local air quality remains an important issue at regional and national scales and, as reported in Ref. [6], only 14% of thermal plants in China were equipped with flue gas desulfurization in 2005. The operation of thermoelectric power plants emits local pollutants that impair air quality. Using the ExternE accounting methodology, which remains one of the leading methods [7], maps the evolution of knowledge about power plant externalities over a

Abbreviations: CCS, carbon capture and storage; FGD, flue gas desulfurization; WW, water withdrawal; WC, water consumption; BAU, business as usual; CL, closed-loop.

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decade and highlights the importance of background assumptions in the results.

The world's growing electric dependency has in parallel led to security concerns as power plants and electrical networks are increasingly viewed as critical infrastructures. Bompard et al. propose a characterization of the different threats to power systems and distinguishes between conventional, natural and accidental threats and unconventional, malicious or emerging threats [8]. Along with the above-mentioned concerns, water withdrawal and consumption for power production is increasingly recognized as another major issue for the power sector. Water management is performed at hydrological basin level and, with increased pressure from electricity demand, concurrent uses and changes in mean and extreme temperatures, its availability for electricity production has evolved from a secondary decision factor to become a potential operational or design constraint. The 2012 world energy outlook issued by the IEA (International Energy Agency) acknowledges its emergence as a top priority for energy specialists [9].

Power systems face multiple challenges; this paper focuses on the water dimension, and addresses the issue by looking at long-term competition between cooling technologies. Indeed, other policy issues relating to the power sector also include a water conservation dimension. Scrubbers are commonly used in the power sector and other industries for air pollution control. They function by spraying a solution of water and additives on exhaust gas for cleaning purposes, and are used in the power sector for SO_2 control (Flue Gas Desulfurization – FGD). The same principle is used to capture CO_2 from exhaust gas. When security and climate change issues are considered [10], the water dimension can in most cases be related to the need for an efficient cooling system to discharge the power plant's waste heat. The evaporative water issue can also be mentioned in the specific case of hydropower dams.

Several past incidents corroborate the vulnerability associated with cooling systems: during the 2003 heat wave in Europe, plants were forced to shut down and in 2011 the Fukushima accident provided a striking example of cascading vulnerability and of the dramatic impact of a cooling system issue. The recent accidental 29-h blackout affecting the pool cooling system at Fukushima in March 2013 again illustrates the criticality of heat rejection at power plants. However, even in standard operational conditions, thermoelectric plants require significant amounts of water.

Many authors have assessed power plant cooling options and water demand, and an extensive literature review of water consumption and withdrawal factors, including data for renewable power plants, can be found in Refs. [11,12]. Fthenakis and Chul Kim extend the computation of the water factor for the US to the full life cycle of power plant technologies [3]. One interesting result of this contribution is the distinction between the relative share of onsite and upstream consumption for the different technologies. Given the growth prospects for electricity and the potential adverse effects of a changing climate, the water impact of power systems in coming decades has also been considered by several authors using different methods.

Feeley et al. were among the earlier estimates of the future water withdrawal and consumption of US thermoelectric plants [13]. This paper combines an exogenous scenario for the development of the US electric system up to 2030 with water use factors and exogenously specified water conservation technology scenarios. 13 technology baskets combined with given market penetration rates from 10 to 50% were used.

Macknick et al. focus on a high sub-national level for the US, and extend their analysis to 2050 [12]. This study assumes the market shares of cooling systems and excludes one-trough systems for new additions. Four electricity supply scenarios are also used as input. The specificity of this study is that it uses a geographically detailed capacity planning model and evaluates water uses at a very detailed hydrologic level.

In Ref. [14] 26 German power plants are analyzed. The author uses a very detailed and thermodynamics oriented approach instead of given water factors. The model uses a daily resolution and computes the efficiency of cooling process via thermodynamic relations linking the plants' output, water temperatures and legal thresholds. The water impact is then calculated based on a regional climate model that downscales IPCC (Intergovernmental Panel on Climate Change) scenarios and a sensitivity analysis of reduced river runoff. However, the long-term projections for 2040 and 2070 are made under an assumption of constant technology, and the plants' operation characteristics and output are not linked to a full future power sector for Germany.

Rübbelke and Vögele conducted a "what-if" analysis for Europe by 2050 involving a typical summer's day and an increase in air temperature [15]. They used simple thermodynamic equations to link water demands to air and water temperature and focus on the supply equilibrium and exchanges for a hypothetical hotter day in 2050. A detailed climate module with a 1 km^2 resolution was used along with water availability scenarios: a status quo, a scenario assuming hotter ambient air but no extension of water intake, and a third scenario also assuming hotter air but with 10% less intake.

Pan et al. investigate water demand along the coal supply chain in China [16]. The study makes exogenous use of the power sector's evolution from the 2010 world energy outlook for China and derives its water impact from consumption factors. The outcomes are then compared with China's Water Plan objectives for 2030.

Few studies have considered the water demand of future power systems at global level. In its 2012 world energy outlook [9], the IEA introduced a chapter dedicated to water impact assessments of its three energy scenarios. The geographical scope covers the world divided into 7 regions. The methodology applied is based on water factors per power plant technology, primarily derived from a literature survey. In Refs. [17], a GCAM integrated assessment model is used, along with water factors assigned to key power plant technologies. The study projects the world's electricity system up to 2095, and the model's regional disaggregation includes 14 regions. Future water factors are given based on an exogenous projected change of the shares of future cooling systems. Kyle et al. use the same methodology as the previous study, with exogenous water factors integrated into GCAM [18]. While Ref. [17] uses a single electricity scenario and different water consumption or withdrawal intensities Ref. [18], also considers a climate policy scenario expressed as a homogenous worldwide carbon tax and selected power technology scenarios.

The analysis proposed here falls into this broad category of studies of future power systems, with a focus on associated water withdrawal and consumption issues. Improvement of water uses in industrial facilities through process integration has been proposed at an operational level using water pinch methods that are derived from heat transfer pinch analysis. The recent work by Klemeš et al. provides a good overview of these operational methods [19]. Based on a detailed description (flow rates, temperature, and concentration) of all sub processes to identify possibility reuse and recycling options, they are oriented towards the identification of alternative network designs. Comparatively we remain at a more strategic level and do not look into the internal detail of the water networks topology; we also explicitly include economic parameters in our model. We highlight here the singularity of a global model with flexible cooling system technology choices. Instead of using fixed water factors, we use a simplified thermodynamic relationship to explicitly relate water use to plants' efficiency, temperature and electricity penalty. These features are integrated into a bottom-up