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# Unexpected water impacts of energy-saving measures in the iron and steel sector: Tradeoffs or synergies?

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## HIGHLIGHTS

- Associated water impacts of individual energy conservation measures were evaluated.
- Water-energy tradeoffs exist in the production process adjustment of iron sector.
- Considering the water impacts can change the priority ranks of technology choice.

## ARTICLE INFO

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## ABSTRACT

Moving towards integrated governance of water and energy requires balancing tradeoffs and taking advantage of synergies through specific technology choice. However, the water-energy conservation relationships of individual conservation measures in industries other than the water and energy sectors have not been investigated in detail. This study develops a hybrid model to estimate the associated water impacts of individual energy conservation measures, using China's iron and steel industry as a case study. The results reveal that water-energy tradeoffs exist in the production process adjustment, which is conventionally promoted as a key energy-saving measure in iron and steel industry. It is found that replacing the Blast Oxygen Furnace (BOF) process with the Electric Arc Furnace (EAF) in 2007 could save 131–156 kg coal equivalent (kgce) (13.2–15.7%) of embodied energy per ton of crude steel (tcs) at the expenses of an additional 2.5–3.9 $m^3$/tcs (10.6–16.4%) of water footprint. Nineteen energy efficiency technologies are studied in this research, and most of them are identified as having water-saving synergies except for the Low Temperature Rolling Technology. Taking these water impacts into consideration can update the priority ranks of the technology choices and inform policy decisions. Although this study focuses on China's iron and steel sector, the methods and analysis can be extended to other countries, sectors, technologies and environmental impacts.

## 1. Introduction

Many environmental problems and sustainability challenges are intrinsically interrelated but have been separately studied and managed for a long time [1]. With the rising awareness of the interconnectedness of environmental and sustainability problems, various researchers have developed nexus frameworks to articulate how one system relies on or has unintended influence on the other [2,3]. The water-energy nexus is a classic example of such frameworks [4]. On one hand, the extraction, processing, and conversion of energy resources require 15% of the global annual water use [5]. The energy sector will be constrained in areas where water scarcity is a serious problem [6,7]. On the other hand, water collection, treatment, distribution and desalination, which use 1.7–2.7% of global annual primary energy [8], are also challenged by energy crises [9]. In light of these interactions, it is crucial to study these water and energy challenges simultaneously rather than dealing with them in isolation.

Moving towards more integrated governance of water and energy systems requires balancing tradeoffs and taking advantage of synergies through informed specific technology choices [10]. Some studies have compared the water (or energy) impacts of various energy (or water) supply alternatives to illustrate which options can facilitate collaborative conservation [11–15]. For instance, it is found that replacing coal-fired power with wind power offers substantial water benefits [16,17]

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while vigorous development of bioenergy will exacerbate local water supply stress [18]. Other recent studies provide pathways to integrate energy and water supply, including co-optimizing economic dispatch of power and water [19] and utilization of renewable energy in desalination facilities [20]. Apart from the supply alternatives, the conservation measures of one resource in the end-use phase also have unintended direct and indirect effects on the demand of the other resource [21]. The direct effects can be synergies [22], or tradeoffs [23,24], which are highly dependent on specific conservation measures. The indirect effects refer to the water (or energy) footprint embodied in the saved energy (or water) [25–27]. For example, when electricity demands in the end-use phase decrease, the water resources needed in the electricity production are simultaneously conserved.

Although existing studies have made commendable contributions to promoting the understanding of the water-energy nexus, there are few guides on how to integrate water and energy conservation through specific technology choice in industrial sectors other than water or energy. This knowledge gap partially results from the lack of an appropriate research tool. In previous studies, tools commonly used for quantifying the conservation nexus are input-output (IO) models [25,26] and process-based analysis [27,28]. The IO model can assess the indirect water (or energy) co-benefits embodied in energy (or water) savings by changing the appropriate element in the direct requirements matrix [25]. This method, however, fails to consider the details of the technology options. Process-based methods on the other hand, can provide details of individual technologies, but the broader input-output relations between the water/energy sectors and other industrial sectors are difficult to portray. Even if data quality and availability are ensured, the incompleteness associated with process-based analysis will still lead to significant truncation errors compared to an IO-based analysis [29].

To minimize these limitations, some researchers have adopted hybrid analyses that combine the input-output model and process-based theory to conduct life-cycle assessment of products [30,31], technologies [32] and policy scenarios [33]. Hybrid analyses have also been applied to the energy analysis of water systems [34] and the water analysis of energy systems [33,35,36]. However, this method has not been developed to analyze the water-energy conservation nexus of individual technologies in sectors other than the water or energy.

To address some of the knowledge gaps mentioned above, this study employs a hybrid tool to assess the unexpected water impacts, including both direct and indirect effects conveyed through the whole supply chain, of individual energy conservation measures in industrial sectors. This tool couples the physical characteristics of individual measures with the input-output relationships among sectors by disaggregating the appropriate sector in an IO table. Beyond the quantitative evaluation, these associated water impacts were incorporated into the cost-effectiveness assessment of energy efficiency measures to update the rank of the technology choice priority. This study will facilitate policy decisions on a more explicit technology path towards integrated water-energy management in industrial production.

Because energy conservation measures vary in different industrial sectors and are hard to comprehensively present in one paper, we take China's iron and steel sector as a case study. China is the largest iron and steel producer country in the world, accounting for about half of total global production [37]. While boosting the Chinese economy as a pillar industry, the iron and steel sector consumes significant amounts of water and energy, accounting for 7% of national industrial water use [38] and 24% of national industrial energy consumption [39]. Under the dual pressures of water and energy conservation [40,41], integrated governance of resource efficiency improvement is required. It is noted that the iron and steel industry has a broad definition, which includes suppliers of iron ore and ferrous scrap, production of pig iron and crude steel, casting of iron and steel, and manufacturing of final products [42]. In this study, when the iron and steel industry is mentioned, it refers only to the iron and steel production process in the iron making sector, steel making sector, and steel processing sector, according to the Standard Industrial Classification in China (GB/T 4754-2011) [43]. Moreover, the production of coke for steel production is also considered while other activities, including supplying raw material and manufacturing ferroalloys, were excluded from the discussion in this study.

## 2. Methodology

### 2.1. Hybrid analysis based on disaggregated input-output table

This study builds an IO-based hybrid model to embed the individual energy conservation measures into the input-output table by disaggregating the target sector. The disaggregation method is based on model III as described by Joshi [31]. A sector, named n, was disaggregated to two sub-sectors, one of which adopts the energy conservation measure of our interest (sector n + 1) while the other sector doesn't. These two sub-sectors are hypothetical and the differences between them are resulted solely from the utilization of the technology. Each energy conservation measure is studied individually.

The key step of disaggregation is deriving a new $(n+1)\times(n+1)$ technical coefficient matrix $\boldsymbol{A}^{new}$ (with elements $a_{i,j}^{new}$), from the original $n\times n$ technical coefficient matrix $\mathbf{A}$ (with elements $a_{i,j}$). The input coefficient from sector $i$ to the original sector $n$ in $\mathbf{A}$ (indicated by $a_{i,n}$) is a linear aggregation of input from sector $i$ to sector n and n + 1 in $\boldsymbol{A}^{new}$ (indicated by $a_{i,n}^{new}$ and $a_{i,n+1}^{new}$), as shown in Eq. (1)

$$a_{i,n} = (1-s)a_{i,n}^{new} + sa_{i,n+1}^{new} \tag{1}$$

where $s$ is the market share (or penetration rate) of the conservation measure in the total output of the studied sector. In addition, $a_{i,n}^{new}$ and $a_{i,n+1}^{new}$ have a linear relationship, which can be quantified according to the direct effects of the conservation measure on the material inputs. For example, if it is known that the material inputs from sector $i$ change by $f_i$ percent when the studied technology is adopted, then the relationship can be shown as in Eq. (2). If the input changes caused by the conservation technology are measured by physical units (i.e. $b_i$ of material inputs from sector $i$ are saved per unit of product in the studied sector), rather than percentage changes, then physical units will be converted into monetary equivalents using the unit price data [44]. In this case, the relationship can be quantified as the form of Eq. (3)

$$\frac{a_{i,n+1}^{new}-a_{i,n}^{new}}{a_{i,n}^{new}} = f_i \tag{2}$$

$$a_{i,n+1}^{new}-a_{i,n}^{new} = b_i * p_i/p_n \tag{3}$$

where $p_i$ and $p_n$ indicate the unit prices of the products in sector $i$ and sector $n$. Combining Eq. (1) with Eq. (2) or (3), the elements of $a_{i,n}^{new}$ and $a_{i,n+1}^{new}$ can be quantified.

Moreover, the purchases of sector $j$ from the original sector n in $\mathbf{A}$ (indicated by $a_{n,j}$) is the sum of purchase from sector n and n + 1 in $\boldsymbol{A}^{new}$ (indicated by $a_{n,j}^{new}$ and $a_{n+1,j}^{new}$). $a_{n,j}^{new}$ and $a_{n+1,j}^{new}$ can be derived from the $a_{n,j}$, following Eqs. (4) and (5).

$$a_{n,j}^{new} = (1-s)*a_{n,j} \tag{4}$$

$$a_{n+1,j}^{new} = s*a_{n,j} \tag{5}$$

### 2.2. Quantifying the life-cycle water impacts using the EEIO model

Beyond incorporating the technology information into the input-output table, we calculated the life-cycle energy and freshwater consumption of individual conservation measures using the environmentally extended input-output (EEIO) model. The EEIO model is an extension of the economic input-output framework which employs physical units to account for interindustry energy flows, resource requirements and environmental impacts. According to the methods described in Miller and Blair [45], the total requirement coefficient matrix