ARTICLE IN PRESS

Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Valuation of water and emissions in energy systems

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HIGHLIGHTS

- Monetizing externalities provides limited control of environmental impacts.
- Propose an approach to determine marginal prices for emissions and water.
- Found that carbon and water prices must increase by two-three orders of magnitude.

ARTICLE INFO

Article history:
Received 18 June 2016
Received in revised form 8 September 2016
Accepted 10 September 2016
Available online xxxx

Keywords:
Combined heat and power
Real-time operations
Water and emissions
Trade-offs
Biogas

ABSTRACT

Price incentives and economic penalties (monetization) are common approaches to control water usage and total direct greenhouse gas emissions (externalities) of industrial systems. We argue that homogenous pricing of externalities provides limited flexibility for mitigating environmental impacts as systems are affected quite differently by externalities. We use trade-off analysis and scalarization techniques to determine marginal prices for water and carbon by taking into account the actual physical and technical limits, stakeholders, and real-time conditions of individual systems. A combined heat and power (CHP) system providing hot water and electricity to a real residential building complex is undertaken as case study to demonstrate and describe these concepts. For this CHP system, we found that carbon prices should be increased by a factor of 14 and water prices by a factor of 217 to achieve an optimal compromise between cost, water use, and emissions. Our results point towards the need to consider alternative pricing schemes such as resource bidding (as is done with electricity) that better capture technology trade-offs and push systems towards their efficiency limits. Therefore, this approach can help stakeholders identifying more effective incentive-based environmental protection instruments.

1. Introduction

Emerging energy systems such as combined heat and power (CHP) installations have much higher resource utilization efficiencies than conventional systems and can help mitigate losses associated to long-distance energy transport and use of fossil fuels [1]. The flexibility provided by these systems allows for the provision of multiple energy carriers (steam, hot water, chilled water, and electricity) to building complexes as those encountered in residential areas, university campuses, and district systems [2]. These systems can run on multiple fuels such as natural gas, diesel, biomass, and biogas [3,4]. The ability to achieve tight energy integration in modern energy systems, however, results in significantly more complex operations and trade-offs. In particular, one should consider strong and dynamic interactions between energy carriers [5,6], trade-off electricity market conditions and local demands [7], capture dynamics of storage [8–10], synchronize the demand patterns of multiple energy carriers [11,12], consider effects of ambient conditions [13], and consider inefficiencies associated to partial load operations and fuel use [14,15].

The generation of greenhouse gas emissions (GHGE) is one of the most important issues affecting the design and operation of energy systems [16,17]. Diverse multi-objective studies have sought to trade-off economic performance and emissions by using economic penalties [18,19] and by using life cycle assessment metrics [20]. A relevant issue is that incentive-based environmental regulation instruments (i.e., tradable emission permits) are still

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http://dx.doi.org/10.1016/j.apenergy.2016.09.030
0306-2619/

Symbols

Index

t	time, h

Parameters

c_p	heat capacity, kW h/kg °C
f_{GHGE}	factor of greenhouse gas emissions, ton CO_2/kW h
PES	price of electricity from the local grid, $/kW h
PHS	price of heat, $/kW h
U	convective factor, kW h/m^2 °C
UCost	unit cost, $/kW h or $/kg
η	efficiency, %
ρ	density, kg/m^3

Variables

A	convective area (storage tank), m^2
Bio	biogas, kW h
Cost	cost, $
F	fuel, kW h
G	water, kg
I	income, $
NG	natural gas, kW h
PL	partial load
Q	heat, kW h
SW	supply of water, kg
T	temperature, °C
TCost	total of operative cost, $
V	volume, m^3
W	electricity, kW h

Acronyms

C	energy sent to housing complex
CHP	combined heat and power
CS	compromise solution
GHGE	greenhouse gas emissions
OM	operation and maintenance
ST	storage tank

not mature, and thus there is significant uncertainty on the effect of such incentives on actual emission reductions achieved by different technologies [21]. This uncertainty might discourage the massive adoption of new fuels and sustainable technologies such as biogas and fuel cells. Biogas from organic waste, in particular, is a renewable fuel that can help offset environmental impacts associated with fossil fuels [22–27]. Despite these benefits, current biogas production costs are not competitive with those of natural gas, thus requiring government incentives to enable deployments [28,29]. Effects of taxes and economic incentives on biogas utilization have been widely studied [30,31].

Controlling and optimizing water use in power generation systems is another pressing environmental issue [32,33]. Diverse studies have focused on addressing energy-water trade-offs in power generation systems [34–36]. Similar to the case of GHGE, properly valuing water is complicated, as dynamic and sensitive trading markets are not well developed or non-existent. As a result, existing water prices can be rather arbitrary and do not necessarily represent a true value for this resource [37].

The standard approach used by stakeholders to control emissions and water use in industrial systems is monetization [38,39]. The reasoning behind this approach is that water and emissions are externalities, which generate unintended costs associated with a primary economic activity [40,41,30]. This monetization approach has been used to control environmental impact in diverse energy systems such as electricity networks [42], hybrid systems [43], wind generation systems [44], and solar plants [45]. A limitation of monetization is that resource prices and penalties are used on a global basis. In other words, a common price for water and emissions is used for a wide range of economic activities of various types and scales (e.g., power generation technologies, agriculture, manufacturing, and buildings). Moreover, since water and emission markets are immature, prices are not a true reflection of value for individual stakeholders (water and emissions are more valuable for certain activities compared to others).

The monetization approach implicitly assumes that increasing the resource price will decrease resource. However, in reality, the impact on controlling the valuation of the externalities will be observed at different price levels for different technologies and with potentially drastic effects due to the presence of system nonlinearities and physical limits. For instance, the effect of resource prices in some systems will only be observed at high prices that other systems might deem uneconomical because their operations might experience extreme sensitivity to resource prices. Moreover, sensitivity to resource prices can drastically change over time due to seasonal and climate variations that might push the system to its physical limits or during maintenance periods where the system is more vulnerable. As a result, systems with small sensitivity to externality prices will have virtually no incentive to reduce environmental impact while systems with extreme sensitivity could be severely affected economically. The inability to control environmental impact in a more uniform and fair manner is problematic from a policy-making and technology development stand-point, given the wide range of types and configurations of modern energy systems.

An alternative approach to control environmental impact is by using system-specific trade-off analysis. This approach would allow stakeholders to value resources based on system-specific physical constraints and real-time operating conditions. In this work, we propose to use scalarization techniques to find *marginal prices* for water and GHGE that push systems to operate at *optimal compromise solutions* that balance economic and environmental objectives given system-specific designs and real-time conditions (e.g.,system size and/or weather) [46–49]. Such marginal prices can be interpreted as resource bidding prices that reflect the true value of water and emissions. We argue that this compromise-based valuation approach thus provides a more efficient mechanism to assess system flexibility, to identify non-intuitive operational policies, and to achieve more realistic and fair reductions of environmental impact. This approach implicitly pushes systems towards their performance limits and true trade-offs. We highlight that the methodology proposed in this work to determine marginal prices for resources is entirely new and can be applied to a wide range of energy systems that seek to trade-off economic performance with environmental impact. We illustrate our developments using a case study that considers a CHP system providing hot water and electricity to a residential housing complex. To achieve high fidelity and realistic applicability of the proposed approach, we use *real data* for weather, prices, and hot water and electricity demands for a building complex located in Mexico. For

Please cite this article in press as: Fuentes-Cortés LF et al. Valuation of water and emissions in energy systems. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.09.030