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Valuation of Water and Emissions in Energy Systems

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Abstract

Pricing, incentives, and economic penalties (monetization) are common approaches to control and improve water usage and total direct greenhouse gas emissions (externalities) of energy and other industrial systems. We discuss that homogenous pricing for externalities provides limited flexibility for controlling and improving environmental impacts as different systems are affected 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 the system at hand. We demonstrate that high water and emission prices might be needed to control and improve the current system of fixed price for externalities. In addition, 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.

Keywords

combined heat and power; real-time operations; water and emissions; trade-offs; biogas

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

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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].

Greenhouse gas emissions (GHGE) are 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 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 to 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 tradeoffs 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, water prices can be rather arbitrary and do not necessarily represent a true value for this resource [37].

The standard approach to control emissions and water use in industrial systems is by monetization [38, 39]. The reasoning behind this approach is that water and emissions are externalities, which generate unintended costs associated to a primary economic activity [40, 41, 30]. This purely 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 use proportionally. 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 and 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 is because 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 central zone of Mexico. For the CHP system under study, 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. Such prices are marginal prices for the CHP system and thus reflect the true value of resources. Such prices, however, would clearly be uneconomical for other technologies; indicating that system-specific trade-offs need to be captured in other systems as well.

The paper is structured as follows. In Section 2 we present a detailed model for a CHP system to illustrate trade-offs between cost, water, and emissions in modern energy systems. In Section 3 we discuss monetization and optimal compromise strategies. In Section 4 we present a case study with real data to illustrate the developments. The paper closes with concluding remarks and directions of future work.

2 CHP System

We consider a CHP system that simultaneously provides electricity and thermal energy in the form of hot water (obtained through heat recovery) to a residential housing complex. As with most residential systems, electricity and hot water demands follow different patterns and are out of phase, which greatly complicates design and operations of CHP systems [50]. The CHP system interacts with the local utility company, which allows the system to sell electrical power surplus or to buy electricity when production of the CHP system is insufficient or when utility prices are more favorable [51]. This interaction is essential because hot water is usually the limiting resource demand. In addition, local electricity prices have an important effect on CHP layout and performance [52].

The CHP system under study is presented in Figure 1. The system includes an internal combustion engine (ICE) and a thermal storage tank (*ST*). The ICE system under consideration can use both natural gas and biogas as fuels [53]. Biogas is in general more expensive than natural gas but can help displace indirect emissions. The thermal storage tank allows synchronization of electricity and thermal energy demands. For instance, it is possible to store the surplus of hot water during periods when electricity demand is far larger than hot water demands. The stored thermal energy can then be used in periods of high thermal demand and/or when it is not convenient to sell electricity to the utility plant [54]. The water is usually stored at high temperature to prevent the onset of pathogenic agents. Consequently, fresh water must be used to regulate the temperature of the delivered water to the residential buildings. In addition, the CHP system uses a water purging system that allows to drain the excess of hot water produced that cannot be stored or consumed [55]. Moreover, purge water temperature must be regulated to be disposed of in the utility system. Water temperature regulation and storage management can thus lead to high water demands, which might constraint system economic flexibility. For instance, at certain times, the CHP system might aggressively seek to sell electricity to the utility but the thermal storage might already at full capacity and thus there might be an incentive to purge excess water. Thermal storage is essential to prevent the ICE system from operating at partial loads, which has a strong effect on fuel efficiency and emissions. In particular, a CHP unit is most efficient at full load operation, but depends on real-time conditions, storage, utility prices, and demands; the CHP operator might seek to sacrifice fuel efficiency and increase emissions in order to increase economic performance [56, 57]. Biogas can help offset the increased emissions at partial load conditions and thus provides flexibility to the system to interact with the utility company.

2.1 Optimal Control Model

We construct an optimal control model to capture water, emissions, and operational cost trade-offs in CHP systems. The model incorporates energy and material balances of the CHP unit and the dynamics of the storage system. We model the interactions with the utility company and we quantify emissions and water use.

2.1.1 Electricity Demands and Grid Interaction—The total electricity demand of the multi-building system (denoted as W_t^D where t is the time instant) is met using a fraction

(W_t^C) of the total electricity production of the CHP unit (W_t^{CHP}). If the CHP system decides not to allocate all of the CHP generation to meet the demand, the system can buy electricity from the local utility company (this amount is denoted as W_t^B). The system can decide to sell some fraction of the electricity produced in the CHP unit to the utility company (we denote this as W_t^S). This logic is modeled using the power balances

$$W_t^D = W_t^C + W_t^B \quad (1)$$

$$W_t^{CHP} = W_t^C + W_t^S \quad (2)$$

These two balances imply the global balance:

$$W_t^D = W_t^{CHP} - W_t^S + W_t^B \quad (3)$$

Where W_t^C is the energy sent to the main costumer C of the CHP system.

2.1.2 Hot Water Demands and Purge—The demand of hot water (G_t^D) is met using hot water from the storage (G_t^{ST}) and cold water from the utility company (G_t^{CW}) at ambient temperature (T_t^{amb}). The cold water is used for regulating the temperature of the hot water delivered to the buildings and to control the temperature of the purging system. The purge and demand temperature is given by T^D , which is typically required to be 50 °C [58]. This logic modeled using the following mass and energy balances:

$$G_t^D + G_t^P = G_t^{ST} + G_t^{CW} \quad (4)$$

$$(G_t^D + G_t^P)T_t^D = (G_t^{ST}T_t^{ST}) + (G_t^{CW}T_t^{amb}) \quad (5)$$

2.1.3 Thermal Storage Dynamics—The storage temperature (T_t^{ST}) and volume level (V_t^{ST}) depend on the inlet stream given by the hot water generated by the CHP unit (G_t^{CHP}), and by the outlet stream from the storage (G_t^{ST}) used for meeting the hot water demand of the building system. We consider convective losses in the system, which are a function of the heat transfer area (A_t^{ST}) and the ambient temperature (T_t^{amb}) [59]. The transfer area is

dynamic, as it depends on the storage level. The storage system dynamics are captured using the following set of equations:

$$\rho(V_t^{ST} - V_{t-1}^{ST}) = G_t^{CHP} - G_t^{ST} \quad (6)$$

$$\rho c_p (V_t^{ST} T_t^{ST} + V_{t-1}^{ST} T_{t-1}^{ST}) = (G_t^{CHP} c_p T^{CHP}) - (G_t^{ST} c_p T^{ST}) - Q_t^L \quad (7)$$

$$Q_t^L = U A_t^{ST} (T_t^{ST} - T_{t-1}^{ST} - T^{amb}) \quad (8)$$

$$A_t^{ST} = 6(V_t^{ST})^{2/3} \quad (9)$$

The water stored in the tank needs to satisfy a minimum temperature, which is usually set to $\underline{T}^{ST} = 70^\circ\text{C}$:

$$T_t^{ST} \geq \underline{T}^{ST} \quad (10)$$

This temperature prevents proliferation of Legionella [60].

2.1.4 Fuel Use and Partial Load Effects—The thermal and electrical efficiencies (denoted as η_t^{Q-CHP} and η_t^{W-CHP}) of the CHP unit are related to the production of heat and power and to the fuel flow as:

$$\eta_t^{Q-CHP} = \frac{Q_t^{CHP}}{F_t^{CHP}} \quad (11)$$

$$\eta_t^{W-CHP} = \frac{W_t^{CHP}}{F_t^{CHP}} \quad (12)$$

The partial load (PL_t) is defined as the ratio of total production of electrical energy (W_t^{CHP}) and the maximum equipment capacity (W):

$$PL_t = \frac{W_t^{CHP}}{\overline{W}}. \quad (13)$$

The effect of the partial load on the efficiency of the CHP unit is modeled using the equation proposed in [61]:

$$\eta_t^{W-CHP} = (0.324 PL_t^2 + 0.44 PL_t + 0.235) \hat{\eta}^{W-CHP} \quad (14)$$

where $\hat{\eta}^{W-CHP}$ is the maximum (nominal) system efficiency. Note that efficiency decreases in a highly non-linear manner with the partial load while consumption of fuel increases. The total fuel consumption (F_t^{CHP}) can be met by natural gas (NG_t) and biogas (Bio_t):

$$F_t^{CHP} = NG_t + Bio_t \quad (15)$$

The partial load has a minimum limit in order to prevent system starvation effects:

$$PL_t \geq \underline{PL}. \quad (16)$$

The total hot water produced (G_t^{CHP}) at temperature (T^{CHP}) is related to the heat production as:

$$Q_t^{CHP} = G_t^{CHP} c_p (T^{CHP} - T_t^{amb}). \quad (17)$$

2.1.5 Total Direct Emissions—The total direct greenhouse gas emissions (GHGE) is calculated for the different fuels according to their corresponding emissions factor (f_{GHGE}):

$$GHGE = \sum_{t=1}^T (f_{GHGE}^{NG} NG_t + f_{GHGE}^{Bio} Bio_t) \quad (18)$$

where T is the final time index.

2.1.6 Total Water Consumption—Total water consumption (SW) accounts for the water used by the CHP unit to run the ICE and for the water used to regulate the temperature before it is sent to the residential buildings and to the purge system:

$$SW = \sum_{t=1}^T (G_t^{CHP} + G_t^{CW}). \quad (19)$$

2.1.7 Total Cost—The total negative revenue (cost) factors income from sales of heat and power, the cost of operation and maintenance, cost of fuel, and purchase of power from the grid:

$$TCost = Cost^{OM} + Cost^{Fuel} + Cost^P - I^W - I^H \quad (20)$$

The revenue of the CHP system is calculated considering the sales of electrical power and thermal energy. The power sales (I^W) include the sales to the building system (W_t^C) and to the external grid (W_t^S). The price is set by a time-dependent tariff (PES_t) provided by the utility company. The total power sales are given by:

$$I^W = \sum_{t=1}^T (PES_t (W_t^C + W_t^S)). \quad (21)$$

The sales of thermal energy (I^H) are given by the total production of heat in the CHP unit (Q_t^{CHP}) minus the convective losses (Q_t^L). The revenue of thermal energy production is determined by the heating price (PHS):

$$I^H = PHS \sum_{t=1}^T (Q_t^{CHP} - Q_t^L). \quad (22)$$

The cost of maintenance of the CHP unit is based on the unitary cost of operation and maintenance associated to the total power production:

$$Cost^{OM} = Ucost^{OM} \sum_{t=1}^T W_t^{CHP} \quad (23)$$

The cost of fuel ($Cost^{Fuel}$) is determined by prices of natural gas (NG) and biogas (Bio):

$$Cost^{Fuel} = \sum_{t=1}^T (UCost^{NG} NG_t + Ucost^{Bio} Bio_t) \quad (24)$$

The total cost of power purchased from the grid at price ($UCost_t^P$) is given by:

$$Cost^P = \sum_{t=1}^T (UCost_t^P W_t^B). \quad (25)$$

3 Valuation Strategies

We consider two different approaches for determining operational policies for the CHP system: 1) *Monetization Approach* and 2) *Optimal Compromise Approach*. One can prove

that both approaches find Pareto optimal control policies for the multi-objective optimization problem:

$$\min (TCost, GHGE, SW). \quad (26)$$

As we will see next, however, the key difference between these approaches is how objectives are scalarized by using different pricing systems.

3.1 Monetization Approach

In this approach, we obtain a single economic objective function that factors in the cost of water and emissions. The total water cost is calculated using the total amount of water supplied to the CHP system multiplied by the unitary cost of water according with local utility companies [62]:

$$Cost^{Water} = \pi^{Water} \cdot SW. \quad (27)$$

The cost of emissions is defined using the total emissions produced by the CHP unit multiplied by a carbon price according with the local policy [63]:

$$Cost^{GHGE} = \pi^{CO_2} \cdot GHGE. \quad (28)$$

This approach finds an operating policy by solving the optimization problem:

$$\begin{aligned} TCostExt &= TCost + Cost^{GHGE} + Cost^{Water} \\ &= TCost + \pi^{CO_2} \cdot GHGE + \pi^{Water} \cdot SW. \end{aligned} \quad (29)$$

An advantage of this approach is that it is easy to implement and analyze from a regulation and system operator point of view [64]. As we have discussed before, however, the prices imposed by local regulations originate from incomplete or insensitive markets and thus are not a true reflection of resource value for the system at hand.

3.2 Optimal Compromise Approach

The optimal compromise approach scalarizes the conflicting objectives by identifying ideal and worst performance points and associated trade-offs for the system at hand. Scalarization uses the coordinates of the utopia point (*UP*) given by $(TCost^{LB}, GHGE^{LB}, SW^{LB})$. These are obtained by individually minimizing each objective while neglecting the rest. The utopia point is not implementable, as the objectives are conflicting, but is used as a reference of ideal performance. Scalarization uses the coordinates of the nadir solution (*NS*) given by $(TCost^{UB}, GHGE^{UB}, SW^{UB})$. These are obtained through the worst case values for the objectives at the utopia point. For example, when minimizing cost individually we will

obtain worst-case values for water and emissions. The nadir point thus implicitly captures the trade-off between objectives [47].

This approach finds an operating policy by solving the optimization problem:

$$\min w_{cost} \frac{TCost - TCost^{LB}}{TCost^{UB} - TCost^{LB}} + w_{GHGE} \frac{GHGE - GHGE^{LB}}{GHGE^{UB} - GHGE^{LB}} + w_{SW} \frac{SW - SW^{LB}}{SW^{UB} - SW^{LB}}, (30)$$

where w_{cost} , w_{GHGE} , and w_{SW} are nonnegative weights that reflect priorities by different decision makers (e.g., different system operators). An important observation is that for the case with $w_{cost} = w_{GHGE} = w_{SW} = 1$, the compromise solution obtained by solving (30) is the *minimum absolute distance solution to the utopia point*. The solution of problem (30) is a Pareto optimal solution for the original multiobjective optimization problem (26).

Consequently, this approach obtains an optimal compromise between the objectives. The distance to the utopia point can be defined using different norms but here we use the one norm because this allows us to establish a direct connection between the optimal compromise and the monetization approach and to compute marginal prices for water and emissions.

As we will see next, a benefit of compromise approach is that it uses the utopia and nadir point to capture system-specific trade-offs. This allow the system to adjust to current operating conditions (i.e., summer vs. winter conditions) and technology specifications (i.e., small vs. large power plants) as opposed to the monetization approach that uses the same price for water and emissions for all technologies and operating conditions.

3.3 Relationship Between Monetization and Optimal Compromise Approaches

The following result relates the solution of the monetization and optimal compromise approaches.

Theorem 1 *The optimal compromise problem (30) achieves the same solution as the monetization problem (29) if the emission and water prices π^{CO_2} , π^{SW} are set to:*

$$\pi^{CO_2} = \frac{w_{GHGE}}{w_{cost}} \frac{TCost^{UB} - TCost^{LB}}{GHGE^{UB} - GHGE^{LB}} \quad (31a)$$

$$\pi^{SW} = \frac{w_{SW}}{w_{cost}} \frac{TCost^{UB} - TCost^{LB}}{SW^{UB} - SW^{LB}} \quad (31b)$$

Proof: Consider the objective function (30). Multiplying through by the constant $(1/w_{cost})$ ($TCost^{UB} - TCost^{LB}$) does not affect the primal optimal solution of the minimization problem. We can thus obtain the form:

$$TCost^{UB} - TCost^{LB} + \frac{w_{GHGE}}{w_{cost}} \frac{TCost^{UB} - TCost^{LB}}{GHGE^{UB} - GHGE^{LB}} (GHGE - GHGE^{LB}) \quad (32)$$

$$+ \frac{w_{SW}}{w_{cost}} \frac{TCost^{UB} - TCost^{LB}}{SW^{UB} - SW^{LB}} (SW - SW^{LB})$$

Factoring out the constant terms we obtain:

$$TCost + \pi^{CO_2} GHGE^{UB} + \pi^{SW} SW + c \quad (33)$$

with π^{CO_2} , π^{SW} defined as in (31) and where

$$c := -TCost^{LB} - \frac{w_{GHGB}}{w_{cost}} \frac{TCost^{UB} - TCost^{LB}}{GHGE^{UB} - GHGE^{LB}} GHGE^{LB} \quad (34)$$

$$- \frac{w_{SW}}{w_{cost}} \frac{TCost^{UB} - TCost^{LB}}{SW^{UB} - SW^{LB}} SW^{LB}$$

is a constant that does not affect the optimal solution of the minimization problem. We thus have that the optimal compromise solution is equivalent to that of the monetization problem for the price definition (31). D

As can be seen, carbon and water prices obtained by scalarization capture system-specific trade-offs (given by the utopia and nadir solutions). Such prices can be seen as *marginal prices* for these externalities. Moreover, such marginal prices achieve an optimal compromise between cost and environmental impact (system operates at the closest Pareto optimal point to utopia). Current water and emission prices and penalties do not capture such system-specific trade-offs and are not likely to achieve such an optimal compromise. In our next case study, we will see that current water and emission prices in fact have limited control on environmental impact. Moreover, we will see that marginal prices for externalities can be extremely high for CHP systems, indicating that the true value of water and emissions in these technologies is indeed very high.

4 Case Study

We consider a residential housing complex comprising of 1,440 households and 7,632 inhabitants. We use an ICE with a total capacity of 100 kWe, efficiencies $\hat{\eta}^{W-CHP} = 37.25\%$ and $\eta^{Q-CHP} = 47.5\%$, and minimum partial load $PL = 0.35$. We use a storage tank with a capacity of 20 m³. The multi-building system is located in the State of Michoacan in Mexico (by the Pacific coast and near the mountains). The climatic conditions in this region are stable throughout the year. Real demand data for electricity and hot water for the buildings is presented in Figures 2 and 3. As can be seen, demands of hot water (Figure 3) and electricity (Figure 2) follow quasi-periodic patterns but are out of phase (hot water demand peaks at the beginning of the day when inhabitants shower while electricity demand peaks at night). Two

cases are presented: Case 1 considers the data for a week during the summer, Case 2 includes the data for a week during the winter. The ambient temperature use for the case study is presented in Figure 4. The temperature in this region is stable during the year. This fact avoids the use of utilities for room heating and air conditioning. The tariff for electricity from the utility company in this region follows the schedule depicted in Figure 5. Water price, carbon price, and emission factors for natural gas and biogas are presented in Table 1. Emission factors consider all the steps associated to the life cycle of the fuels [65]. The biogas available for the system is estimated based on the organic waste produced by the population of the housing complex [22]. Table 1 presents the local carbon price and the local price of water.

The optimization models were implemented on the mathematical modeling language JuMP [69] and solved with IPOPT [70]. All scripts are available at <http://zavalab.engr.wisc.edu/data>.

4.1 Comparison of Water, Emission, and Cost Objectives

In Figure 6 we visualize cost (TCost), GHG emissions (GHGE), and water consumption (SW) for different operational policies. In particular, we present the location of the compromise solution (CS), the monetization solution (TCostExt), the utopia point (UP), and the nadir point (NP) for Case 1. Table 2 shows the objective values for all of these solutions. The points in the Pareto diagram (Figure 6) corresponds with the minimization process of the objective functions of Total Cost ($TCost$, equation 20), CO₂ Emissions ($GHGE$, equation 18), water consumption (SW , equation 19), compromise solution (CS , equation 30) and monetization ($TCostExt$, equation 29). Utopia Point (UP) corresponds to the lower bounds of the functions TCost, GHGE and SW; Nadir Solution (NS) corresponds to the upper bounds of the same functions (See Section 3.2).

We first note that the utopia point has a total cost of \$3,803, generates 13.29 tons of GHGE, and consumes 459,728 kg of water. The nadir point exhibits costs of \$5,968 (56.9% larger than the utopia point), generates 17.5 tons of GHGE (28.3% larger than utopia), and consumes 474,013 kg of water (3.11% larger than utopia). This illustrates that a dramatic effect in cost is observed when the environmental objectives are fully minimized. Note that the large increase in cost is disproportionate to the relatively small change in water use relative to the utopia point (this indicates that water is highly valuable). The change in emissions is more perceptible, indicating less sensitivity to carbon prices.

We now compare objectives for different operational policies. We note that minimizing total cost (TCost) results in the highest emissions and water use. This is expected, as this policy fully neglects environmental impacts. Interestingly, we note that minimizing the total cost plus externalities (TCostExt) does not affect emissions compared to the policy obtained by minimizing total cost (TCost). This illustrates that the carbon price has virtually no impact on emissions. The compromise solution (CS), on the other hand, reduces emissions quite drastically. In particular, the relative difference in emissions with respect to utopia is 18.6% while those obtained by minimizing TCost are 28.6%.

We observe that fully focusing on water use (SW) has a strong influence on the total cost. In particular, cost increases by over 53.9% compared to utopia point and the minimum cost solution. This again illustrates that water is an extremely valuable resource in this system. Interestingly, the water price used in TCostExt does control water use but the control is limited compared to that compromise solution. In fact, the *compromise solution achieves the same water use as the utopia solution*. The cost increase for the compromise solution is only 7.9 % (as opposed to the 53.9% obtained with the policy solution obtained by fully minimizing water). This illustrates that it is possible to find an operating policy for the CHP system that can fully minimize water use without reaching the worst-case cost.

An important conclusion is that *water and carbon prices in this region provide virtually no incentives to reduce environmental impact*. This can be seen when we compare the total cost plus externalities obtained with the TCostExt, TCost, and CS policies. In particular, note that the TCost policy achieves essentially the same cost plus externalities (\$4,812) as the TCostExt policy (\$4,806). Note that the CS policy increases total cost plus externalities (\$5,051) by only 4% compared to the TCostExt solution while drastically reducing emissions and fully minimizing water use. This illustrates that the compromise approach can thus identify high-quality and non-intuitive trade-offs by better exploiting system flexibility. We discuss such non-intuitive policies next. Results for Case 2 (winter) are presented in Table 3. We highlight that the cost and water usage of the utopia point for Case 2 are very different from those of Case 1. We note that the monetization approach (TCostExt) does not improve the emissions compared to Case 1 but the scalarization approach (CS) does. This illustrates that trade-offs in water, cost, and emissions change seasonally and that the scalarization approach can adapt accordingly.

4.2 Comparison of Operational Policies

We now compare key operational variables obtained with different policies and we focus on the summer case. Figure 7 shows the electrical power output of the CHP unit. Under the monetization approach, the system operates at full load all the time. The reason is that, by doing so, it maximizes electricity sales to the utility company. This operational policy is typical in CHP facilities. By operating at full capacity, however, the system generates excess hot water that needs to be purged, increasing water use. This is observed in Figure 8. The compromise solution reduces electricity production in periods of low thermal energy demand and increases it during peak hours. This allows the system to save water by better managing the storage system (observed in lower peaks of storage and towards the end of the horizon).

Figure 9 shows the behavior of the water demand of the CHP system (this includes the water used in the CHP unit itself and the water used for regulating the temperature for the purge and for the final user). We note that during peak hours both strategies have similar water demands, but during hours of low consumption, the compromise solution uses less water than the monetization approach. We note that the total water savings obtained with the compromise solution compared to the monetization approach are nearly 5,000 kg/day, which translate to up to 450,000 gallons/year.

CHP emissions are linked to fuel use and partial load operation. Figure 10 shows the behavior of the emissions for the monetization and compromise approaches. It is clear that the compromise solution drastically reduces emissions and tends to operate the system in a more flexible way by decreasing CHP load. This is enabled by the optimal use of biogas. To see this, from Figure 11 we note that the monetization approach uses no biogas, as the fuel cost is much higher than that of natural gas. This indicates that the current carbon price does not seem to incentivize biogas use. The compromise solution uses biogas to displace emissions associated to partial load operation. This can be used to reduce CHP power generation capacity in periods of low thermal demand and with that save water. This is the main reason why the compromise solution achieves the same water use as the utopia solution. This illustrates the non-obvious coupling between water usage and emissions. In particular, from Table 2 we can see that minimizing water use (the SW solution) reduces emissions.

4.3 Water and Carbon Marginal Prices

We now compute the water and carbon marginal prices needed for the monetization approach (TExtCost) to yield the same solution as the scalarization approach (CS). The prices are computed using the results of Theorem 1 and the values of the utopia and nadir points reported in Table 2. We obtain:

$$\Pi^{CO_2} = \frac{\$5,968 - \$3,803}{17.05 \text{ ton } CO_2 - 13.29 \text{ ton } CO_2} = 575\$/\text{ton } CO_2 \quad (35)$$

$$\pi^{SW} = \frac{\$5,968 - \$3,803}{474,013\text{kg} - 459,728\text{kg}} = 150\$/m^3. \quad (36)$$

By comparing these values with the prices reported in Table 1 ($\pi^{CO_2} = 40 \text{ \$/ton } CO_2$ and $\pi^{SW} = 0.69 \text{ \$/m}^3$) we can see that the carbon price should increase by a factor 14 and the water price by a factor 217 (compared to the current local prices) for the CHP system to achieve the same solution as the optimal compromise approach. These prices, while high, are a true reflection of the value of water and emissions for this technology. This illustrates how the optimal compromise approach can enable price discovery for resources in different technologies. We recall, however, that the high marginal prices only lead to a total increase of 4% of the total cost for the CHP system relative to the monetization approach. The high marginal prices of the CHP system, however, would clearly be uneconomical for other industrial activities such as agriculture or manufacturing. This clearly illustrates the need for policies that promote system-specific resource valuation and trade-off analysis.

The implementation of new policies to promote more efficient use of basic resources by industrial systems is nontrivial and require of careful considerations [71]. One could envision the creation of organized competitive markets in which systems bid for resources, as is done in electricity markets. In such a setting, systems will have an incentive to trade-off resource use with their actual products and thus generate more realistic marginal prices that

reflect the true value of water and emissions in their system. Implementing such markets is allowing them to mature, however, can take a significant amount of time. A less desirable but faster alternative could be to develop regulations that ensure that industrial systems operate at points that truly reflect a compromise between productivity and resource use. The proposed methodology can thus help government agencies such as the US Environmental Protection Agency to promote more sustainable and healthy communities that are aware of strong economic and environmental trade-offs that exist in infrastructure systems and that are aware of health impacts associated to emissions in both rural (e.g., by recovering methane from organic waste) and urban areas (e.g., by decreasing emissions of power plants in concentrated urban spaces). To achieve this, diverse policy mechanisms, technologies, and systems need to be evaluated in order to ensure that they meet desired targets. One of the most promising technologies to achieve these goals is CHP systems, which exhibit a wide range of configurations ¹. During the last decades, there have been improvements and new developments in CHP systems in terms of power, efficiency, durability, emissions, and time/cost to market ². These improvements have been achieved by collaborative research efforts from private industry, universities, and the federal government. In addition, some of these Public-private partnership programs include the US DOE CHP Deployment Program and the US EPA CHP Partnership ³. For example, the EPA program works with stake-holders to minimize air pollution and water consumption related to power generation, heating, and cooling needs by promoting the use of CHP. In addition, EPAs goal is to eliminate policy obstacles by promoting the economic, environmental, and social benefits of CHP systems. Therefore, the techniques proposed can support these efforts in performing a systematic evaluation of CHP technologies by providing scientific foundations for efforts to modify and improve federal and state policies and incentives for CHP systems (e.g., alternative pricing for externalities) ⁴. These will be reflected in cost-effective reductions in emissions that contribute to global warming (e.g., carbon dioxide, methane), emissions of criteria air pollutants (carbon monoxide, nitrogen oxides, and sulfur dioxide), reduced need for local power plant and infrastructure (e.g., transmission, distribution), particular matter, and increased energy efficiency. In addition, the level of interest of urban and rural communities and government can be easily incorporated into the proposed framework by using multi-stakeholder formulations [72]. This becomes relevant when consider large industrial systems (power plants) that affect large populations.

5 Conclusions

In this paper, we use multiobjective optimization techniques to argue that monetization of water use and emissions have limited impact on controlling environmental impact. In particular, we argue that when the same resource prices are used for drastically different industrial activities, they do not properly capture system-specific trade-offs and are thus not a true reflection of resource value. We use trade-off analysis and scalarization techniques to show how to identify marginal prices for resources that capture system-specific performance

¹https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf

²<http://energy.gov/eere/amo/chp-deployment>

³<https://www.epa.gov/chp>

⁴<https://www.epa.gov/chp/dchpp-chp-policies-and-incentives-database>

limits. Using a CHP system that incorporates real demands for a residential housing complex, we found that emission prices must be increased by a factor of 14 and water prices by a factor of 217 to achieve an optimal compromise between cost, water, and emissions. These high marginal prices reflect the marginal prices of resources for the CHP system. Our results point towards the need to consider different resource valuation policies that better capture system-specific trade-offs (such as resource-bidding systems in organized markets). In addition, it would be of interest to compute resource marginal prices for other energy technologies in order to establish systematic comparisons, better guidances for policy-making and resource pricing, and identify system designs that minimize resource marginal prices.

Symbols

Index		
Symbol	Description	Units
t	Time	h
Parameters		
c_p	Heat Capacity	kWh/kg °C
f_{GHGE}	Factor of Greenhouse Gas Emissions	ton CO ₂ /kWh
PES	Price of electricity from the local grid	\$/kWh
PHS	Price of Heat	\$/kWh
U	Convective factor	kWh/m ² °C
$UCost$	Unit Cost	\$/kWh or \$/kg
η	Efficiency	%
ρ	Density	kg/m ³
Variables		
A	Convective Area (Storage Tank)	m ²
Bio	Biogas	kWh
$Cost$	Cost	\$
F	Fuel	kWh
G	Water	kg
I	Income	
NG	Natural Gas	kWh
PL	Partial Load	
Q	Heat	kWh
SW	Supply of Water	kg
T	Temperature	°C
$TCost$	Total of operative cost	\$
V	Volume	m ³
W	Electricity	kWh
Acronyms		
C	Energy sent to the main costumer (Housing Complex) from the CHP unit	
CHP	Combined Heat and Power	
CS	Compromise Solution	

GHGE	Greenhouse Gas Emissions
OM	Operation and Maintenance
ST	Storage Tank

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Figure 1:
Sketch of CHP system.

Figure 2:
Electric power demand dynamics for buildings.

Figure 3:
Hot water demand dynamics for buildings.

Figure 4:
Local ambient temperature.

Figure 5:
Tariff schedule for electricity from the utility company.

Figure 6:
Cost (TCost), emissions (GHGE), and water (SW) trade-offs for different operational policies.

Figure 7:
CHP load operational policy.

Figure 8:
Storage volume policy.

Figure 9:
Water consumption of CHP system.

Figure 10:
GHG emissions.

Figure 11:
Biogas demand.

Table 1:

System data [66, 22, 67, 68].

Parameter	Value
Emissions factor (natural gas)	380 g CO ₂ /kWh
Emissions factor (biogas)	44 g CO ₂ /kWh
Fuel cost (natural gas)	0.013 \$/kWh
Fuel cost (biogas)	0.034 \$/kWh
Water price	0.69 \$/m ³
Carbon price	40 \$/ton CO ₂
Thermal energy price	0.015 \$/kWh
Biogas capacity	24,129 kWh

Table 2:

Objective values for different operational policies (Case 1 - Summer).

Objective Minimized	Objective Values				% Distance to UP		
	TCostExt (\$/week)	TCost (\$/week)	GHGE (tons)	SW (kg)	TCost	GHGE	SW
TCost	4,812	3,803	17.05	474,013	0	28.3	3.11
GHGE	6,818	5,968	13.29	462,944	56.9	0	0.7
SW	6,768	5,854	14.91	459,728	53.9	12.2	0
TCostExt	4,806	3,803	17.05	465,036	0	28.3	1.15
Compromise Solution (CS)	5,051	4,104	15.76	459,751	7.9	18.6	0
Utopia Point (UP)	-	3,803	13.29	459,728	-	-	-
Nadir Point (NP)	-	5,968	17.05	474,013	56.9	28.3	3.11

Table 3:

Objective values for different operational policies (Case 2 - Winter).

Objective Minimized	Objective Values				% Distance to UP		
	TCostExt (\$/week)	TCost (\$/week)	GHGE (tons)	SW (kg)	TCost	GHGE	SW
TCost	4,325	3,348	17.05	436,206	0	28.4	6.52
GHGE	6,101	5,270	13.29	414,942	57.4	0	1.33
SW	6,272	5,407	14.56	409,508	61.5	9.6	0
TCostExt	4,317	3,348	17.05	436,206	0	28.4	6.52
Compromise Solution (CS)	4,403	3,348	16.48	426,697	0	6.8	4.2
Utopia Point (UP)	-	3,348	13.29	409,508	-	-	-
Nadir Point (NP)	-	5,407	17.05	436,206	61.5	28.4	6.52