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Modeling marginal CO_2 emissions in hydrothermal systems: Efficient carbon signals for renewables

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HIGHLIGHTS

- Transmission congestion and hydro storage constraints impact CO_2 abatement.
- Proposed model calculates marginal prices and carbon emissions in space and time.
- Neglecting transmission and storage hinders efficiency of CO_2 abatement policies.
- More accurate assessment of emission abatement of renewable projects is provided.
- Marginal CO_2 metrics for hydrothermal systems extensible to other types of storage.

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ABSTRACT

Reducing local and global emissions is one of the drivers behind the promotion of renewable energy technologies (RETs). Some RET projects (e.g. solar, marine power, and some biomass and wind) usually require supplemental income from carbon credits in order to make them economically viable. This paper presents the mathematical development of nodal marginal CO_2 emission metrics for hydrothermal systems. These metrics are obtained from optimal power flow and hydrothermal dispatch models considering hydro uncertainty. The proposed model allows a more accurate assessment of the emission reduction effect of RET projects and the provision of efficient carbon signals to the system. Modeling of hydro reservoirs and intertemporal constraints also allows incorporating the emission mitigation potential of water storage. The concepts of marginal CO_2 emissions for hydrothermal systems are first exemplified using a small test system, and then simulations on a real hydrothermal system illustrate how these metrics can inform investment and operational decisions. Theoretical and simulation results show that transmission and hydro storage constraints neglect may provide wrong signals for RET investors, missing the incentives to install in areas where the potential for emissions reduction is higher (where renewable energy displaces a larger amount of coal or diesel). Policy makers can use the proposed model to assess the cost-effectiveness of emission reduction policies.

1. Introduction

The energy sector is responsible for a large part of *greenhouse gases* (GHG) emissions leading to anthropogenic climate change [1–3], with about a quarter of worldwide CO_2 emissions in 2010 coming from electricity and heat [4]. A number of measures, both local and global, have been taken to reduce GHG emissions in the energy sector, including the *Clean Development Mechanism* (CDM) of the Kyoto Protocol [5], *Renewable Portfolio Standards* [6], and *Cap-and-Trade* [7–8]. Identifying the entities responsible for GHG emissions and properly estimating them is important to evaluate the effectiveness of mitigation policies. Fuel-fired generation technologies (e.g. coal, gas, and diesel power plants) are the main culprits of GHG emissions in the electricity sector and replacing them by *Renewable Energy Technologies* (RET, e.g. hydro, wind and solar power plants) can help reduce global emissions [9]. However, the location of a RET project can greatly affect the amount of emissions it can abate [10,11]. As methods for estimating GHG emissions do not always factor in operating practices or transmission constraints

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of electric power systems, they may fail at promoting the most efficient projects in terms of climate change mitigation.

Currently, there is no agreement on the most appropriate methodological approach to evaluate emissions from specific sources [12,13]. Furthermore, to estimate emissions attributable to specific electric loads or the abatement potential of emission reduction policies, regulators and researchers can choose from a number of different models, methods, and metrics. A key modeling choice is to use either average or marginal emission intensities [12–14]. According to results in [12], differences of up to 68% across average and marginal emission factors can be detected depending on the method used. The use of both types of CO_2 intensities for power generation is compared in [14]. They estimate reductions from electricity savings using both types of metrics and report that average emission factors can present serious shortcomings for this type of study. As pointed out in [15], metrics based on average emission factors assume that all generators in the system respond proportionally to a generation/demand change. In reality, emission reductions in short-run studies depend on the generators currently committed and their operational margins, while in long-run studies depend on the generators whose construction would no longer be needed [14].

In recent years, a great deal of work has been aimed at estimating the impacts of both temporal and spatial heterogeneity of electricity production and consumption on GHG emissions and their mitigation, recognizing the importance of *when* and *where* electric energy is generated or consumed for estimating emissions. On the one hand, disaggregated temporal patterns are important to properly calculate the emission abatement potential of: (a) renewable energy projects (e.g. wind and solar [16,17], (b) emerging technologies on the consumer side such as demand response and electric vehicles [13,18,19], and (c) energy storage and reserves [19–22]. On the other hand, spatial disaggregation of emissions may be quite important to identify potential sites for investment [10,11]. As discussed in [11], lower-quality solar resources may abate more emissions than sunnier sites when the characteristics of the power grid are considered. Spatial disaggregation is also relevant to evaluate the impact on emissions of electricity trade and power exchange between interconnected areas [22,23]. However, using a regional/national spatial resolution as in [22,23] may be insufficient if there is significant transmission congestion within the interconnected areas.

Ideally, one should disaggregate emissions at least hourly and at the bus level. Accordingly, some authors have recently extended concepts from *Locational Marginal Pricing* (LMP) in electricity markets [24] to marginal emissions. For example, a load reallocation scheme for reducing pollution informed by *Locational Marginal Emissions* (LME) is proposed in [25]. In [26], Ruiz and Rudkevich suggest that carbon emissions of an electric system vary both temporally and spatially due to the use of diverse generation technologies, transmission constraints, and chronological changes in the demand. They suggest using *Marginal Carbon Intensities* (MCI) of a bus and *Shadow Carbon Intensities* (SCI) of a transmission constraint to recommend specific locations where to invest for mitigating GHG emissions. They apply this concept in [23] to define the optimal investment policy underlying Renewable Portfolio Standards (RPS) and show that existing RPS policies are suboptimal to reduce GHG production. In [27], the implications of that suboptimality is explored for operations, planning, and policy making using temporally and spatially disaggregated marginal carbon metrics. In [28] the authors propose and test a rapid approach for estimating marginal emissions directly from LMPs, and pinpoint the potential of systems with large hydro to temporally shift energy use to reduce emissions, but without further exploration. A different approach is taken in [29], where satellite imagery is integrated with statistical data to model CO_2 emission dynamics in China with higher spatial and temporal resolution.

The use of marginal carbon signals in hydrothermal systems is more challenging than for mainly thermal power systems due to: (1) the capacity to store large amounts of energy in water reservoirs and (2) hydrological uncertainty. First, the ability to store energy causes time-coupling of dispatch decisions, adding complexity to the models [30–32]. Second, hydro uncertainty leads to deciding on the present use of stored water without knowing its future availability. In hydrothermal systems, both features need to be addressed as they may have a significant impact on energy prices and carbon emissions. The main contribution of this paper is to address theoretical and practical issues concerning the calculation of marginal emission factors, disaggregated both spatially and temporally, for hydrothermal systems. These carbon signals can be used to inform investments both in RET generation projects and transmission congestion relief. Furthermore, studying the use of marginal emission metrics in hydrothermal systems may shed light on the impacts of energy storage and uncertainty in other types of systems, especially considering the growing interest in emerging bulk energy storage technologies and the rising penetration of variable renewable generation.

This paper presents a methodology to calculate values of marginal CO_2 emissions in hydrothermal power systems. This methodology allows modeling the economic and environmental impacts of energy policies, RET project, and transmission investments in the electricity sector. For this purpose, the methodology proposed in [26] for a thermal system is extended using theoretical insights of hydrothermal systems operation [31,32]. Thus, we propose a model of optimal dispatch to calculate marginal emission values disaggregated in space and time considering both the transmission system and the time-coupling of decisions in hydrothermal systems. The relevance of the mathematical modeling and the proposed marginal emission metrics go beyond their application to hydrothermal systems, as they are also suitable for other systems with transmission congestion, for different types of uncertainty, and for different types of storage.

This paper is structured in six sections. Section 1 presents a basic optimal dispatch model of hydrothermal systems. Section 2 defines some marginal emission metrics in the context of hydrothermal systems. Section 3 illustrates and validates these concepts through a small test case. Section 4 discusses the application of marginal CO_2 metrics to a real hydrothermal system, emphasizing how they can be used to provide efficient carbon signals for renewable energy investments. Finally, Section 5 presents the conclusions of this paper. A nomenclature section is provided in the Appendix A.

2. Modeling of hydrothermal power systems

Hydrothermal power systems have the ability to replace thermal by hydro generation in certain periods, reducing operating costs. In general, hydro power shows a *peak shaving* effect by generating during the hours of higher price/demand to displace the most expensive thermal generation. The *Present Operating Cost* (POC) of the system decreases when more stored water are used, reducing hydro energy availability in the future and increasing the *Future Operating Cost* (FOC) of the system. As Fig. 1 shows, the optimal use of stored water is achieved when the marginal savings of using one more unit of water in the present is equal to the marginal cost of not having that unit of water in the future (*strategic value of water* γ). As water in reservoirs replace thermal generation (leading to a reduction of carbon emissions), we define the *Marginal Water Emission Value* (MWEV) as the marginal reduction in the system's carbon emissions as a result of using an extra unit of stored water.