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A spatially-resolved inventory analysis of the water consumed by the coal-to-gas transition of Pennsylvania

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ABSTRACT

Life cycle assessments (LCA) typically exclude spatial information in estimating the water consumption associated with a product, resulting in calls to improve regional detail to better reflect spatial variation. In response to these calls, we have compiled a spatially-resolved inventory of changes in water consumption associated with the coal-to-gas transition in Pennsylvania at the resolution of watersheds from 2009 to 2012. Results indicate that the total water consumption of the fuel extraction and power sectors in Pennsylvania increased by 7.6 million m^3 (2 Bgal) over four years. At the state and watershed scales, we compare total water consumption for the coal-to-gas transition to a case where only the water consumed across two life cycle stages of electricity generation is considered – fuel extraction and use at the power plant to generate electricity. The results for the latter indicate that water consumption decreased by over 15.1 million m^3 (4 Bgal). For both cases, watershed-level results showed water consumption generally increased in watersheds with growing shale gas activity or new natural gas capacity, while it decreased with diminishing coal-fired generation. Watershed-scale water consumption from 2009 to 2012 may be reversed from a net increase to decrease (and vice versa) when the total water consumption is compared to the water consumed specifically for life cycle stages of electricity generation, reinforcing the importance of further developing spatially-resolved inventories for LCA. Focusing on the water consumption associated with only electricity generation and its fuel use does not capture the full effects of fuel extracted for use in other sectors. We suggest that spatially-explicit inventories that include multiple life cycle stages should be a critical component in the development of more comprehensive, spatial LCA methodology. Spatial differentiation in inventories is necessary to adequately characterize watershed-level impacts that can be normalized over a functional unit. The approach can be used as a complementary assessment to LCA that can inform policy-makers and investors about where energy developments may pose additional risks to water supply and availability.

1. Introduction

The coal-to-gas transition in Pennsylvania has resulted in changing spatial patterns of water consumption from 2009 to 2012 (Patterson et al., 2016). Life cycle assessment (LCA) is a method for examining the environmental burdens associated with a particular product or process from materials extraction to waste disposal (cradle to grave) (Reap et al., 2008), where environmental burdens can include resource demands such as water use (Ekvall and Finnveden, 2001). For such assessments, water use is categorized as either water consumption (water that is removed from a source and not returned), or water withdrawals (water diverted from a source regardless of whether it is later returned) (e.g. (Jordaan et al., 2013)). LCA is often used to evaluate differences in water consumption across energy technologies, but it does not capture the changing spatial patterns of water consumption (Grubert et al., 2012; Clark et al., 2013; Meldrum et al., 2013). The need to further develop dynamic, spatially-resolved LCA has been noted, particularly to better represent the spatial variation in product flows and the heterogeneous patterns of environmental impacts (Reap et al., 2008; Yang, 2016). Spatial differentiation within LCA

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would enable a more comprehensive understanding of localized impacts, such as those that might occur from water consumption.

LCA comprises of four iterative stages: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation (International Organization for Standardization (ISO), 2006). During the goal and scope definition, the product or process in question is identified along with the objective of the study, the system boundaries of the LCA are delineated, and the functional unit is defined. The functional unit serves as a normalization factor for the environmental burden being assessed, providing a reference to which the system's inputs and outputs are related (International Organization for Standardization (ISO), 2006). The inventory analysis involves data collection and analysis necessary to quantify relevant inputs and outputs of the product or process in question. The impact assessment involves an evaluation of the environmental significance of the impacts resulting from the inventory results. Finally, the interpretation stage involves an evaluation of results relative to the goal and scope of the study in order to generate conclusions and/or recommendations about the product system for decision-makers (ISO, 2006). We suggest that to characterize the impacts from water consumption per functional unit at scales relevant to water management decisions, inventories must be spatially differentiated. With spatial disaggregation at the resolution of watersheds, different impacts associated with water consumption that are typically evaluated in LCA (e.g. water stress (Pfister et al., 2011) or scarcity (Quinteiro et al., 2017)) may be calculated such that spatial patterns of water consumption can be recognized. Once a watershed-level impact assessment is complete, results may be normalized over a functional unit, creating a more concrete connection between spatial differentiation in the inventory analysis stage with the impact assessment stage of LCA.

While LCA results typically exclude spatial and temporal information (Reap et al., 2008), methods and data are evolving to better incorporate spatiotemporal factors (Jordaan et al., 2013; Grubert et al., 2012; Mutel et al., 2011; Scown et al., 2011; Berger and Finkbeiner, 2010; Hellweg, 2014) with the increased use of tools such as Geographic Information Systems (GIS) (Patterson et al., 2016; Jordaan et al., 2013; Mutel et al., 2011; Hellweg, 2014). Life cycle inventories are more commonly considering site-level differences; however, the estimated impacts remain spatially-aggregate without the spatial differentiation of the site-level inputs (Şengül et al., 2016; Siddiqui and Dincer, 2017). While less critical for unconstrained environmental burdens such as the release of carbon dioxide, the inclusion of geographical variation is crucial when considering spatially bound resources and impacts (Tessum et al., 2012), such as those related to water (Koehler, 2008). Unlike greenhouse gas emissions, surface water and the impacts of its consumption are spatially constrained to the watersheds from which the water is withdrawn. LCA research to date, however, has been criticized for putting less weight on the spatial differentiation of water consumption when compared to the potential impacts to ecosystems (Hoekstra, 2016). One regionalized study of electricity generation in the United States has shown that important differences exist between site-generic and regional methods, but only one life cycle stage was evaluated (electricity generation) (Mutel et al., 2011). Site-level power plants were evaluated to link the inventory analysis to the impact assessment. Spatially differentiated analyses of water consumed by power generation alone are commencing to emerge (Peck and Smith, 2017; Peer et al., 2016; Peer and Sanders, 2017); however, LCAs that compare water consumption of coal- and natural gas-fired power continue to remain spatially aggregated without geographic boundaries (Clark et al., 2013; Meldrum et al., 2013) or at state (Grubert et al., 2012; Jiang et al., 2014) and national scales (Chang et al., 2015). Thus far, LCAs have yet to comprehensively include spatially-differentiated water consumption for electricity generation in the inventory analysis stage that includes the extraction of fuel consumed by power plant operations at ecologically-relevant scales (Grubert et al., 2012; Clark et al., 2013; Pfister et al., 2017).

To contribute to the development of spatially explicit LCA methodology for water consumption, we focus specifically on developing a spatially-resolved inventory of the water consumed by two life cycle stages of electricity generation at the resolution of individual sites (fuel extraction and power plants) in the state of Pennsylvania, with results aggregated to the scale of watersheds. While the scale of watersheds has been noted as a logical choice for LCA (Hellweg, 2014), inventory analyses have not yet been developed at this spatial resolution in a way that can be used to uncover differences in consumption and impacts across regions (Koehler, 2008). For example, Grubert et al. (2012) considered how estimated ultimate recovery across shale gas basins may influence the water intensity of the fuel extraction stage of the life cycle of power generation; however, the life cycle results were neither spatially differentiated nor evaluated at ecologically-relevant scales such as watersheds. The inventory developed in this paper includes the monthly and annual water consumption for the coal-to-gas transition in Pennsylvania from 2009 to 2012 for each watershed (defined as HUC8 sub-basins – see Supplementary Material), providing a way in which spatial differentiation in inventories can contribute to the further development of assessments of the life cycle water consumption of products. Our contribution is two-fold. First, we develop an inventory as a step towards spatially-resolved LCA that complements present methodology with more detailed information about the spatial variability of water consumption. In particular, our watershed level assessment indicates that the coal-to-gas transition has had different impacts on water consumption across watersheds – a fact that is not yet well-captured within LCA methodology to date due to resource and data limitations. Estimates for water consumption by watershed can reverse or become less pronounced when the boundaries are limited to power generation and the fuel consumed in the state to generate electricity. Second, the inventories provide a useful accounting method for policy-makers and investors to better understand the changing spatial patterns of the water consumed by major technological transitions.

1.1. The water implications of the coal-to-gas transition

One of the key drivers of the coal-to-gas transition in the power sector of the United States (Wigley, 2011) is the development and diffusion of shale gas extraction via hydraulic fracturing technologies. The coal-to-gas transition and its potential impact on water resources is prominent in areas of the United States where the role of natural gas for power generation has increased relative to coal, such as in Pennsylvania (Patterson et al., 2016; Wigley, 2011). The national water consumption of shale gas extraction (estimated to be at most 31 Bgal/year from 2012 to 2014 (Kondash and Vengosh, 2015)) is small compared to that of power generation. Estimated water consumed for thermoelectric power generation in 2010 was 1278 Bgal/year (Kondash and Vengosh, 2015). The related assessments of water consumed in the coal-to-gas transition have been limited in capturing spatially heterogeneous and temporally dynamic changes (e.g. Grubert et al. (2012) recognized differences in shale gas basins but life cycle results remained spatially aggregate).

Important differences exist between site-specific, regional, and site-generic results for LCA of power generation (Patterson et al., 2016; Mutel et al., 2011), pointing to the critical need to incorporate higher resolution spatial estimates of water consumption resulting from the deployment of new energy technologies to