Final Report: Addressing the Water-Energy Nexus of Fossil Power Generation by Considering Technological, Agro-Ecological, and Economic Options in the Muskingum Watershed

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1   Problem and Research Objectives

Thermoelectric power plants generate electricity and flue gas scrubbers mitigate emissions from the plants. However, at the same time, these plants withdraw large quantities of water from the watershed. In the United States, this withdrawal corresponds to 45% of the total 2010 water use [1]. In addition, NO_X emissions from the scrubbers cause deposition of excessive nutrients in the watershed. Therefore, increasing electricity generation could increase water stress, deteriorate water quality, and contribute to climate change. Also, in the watershed where power plants are located, other activities, such as farming, interact with the power plants since these activities also require water from the watershed as well as energy from the power plants and release nutrients to the watershed. To prevent shifting of environmental impacts across multiple flows [2], the energy-water nexus between different activities in the watershed needs to be understood in assessing the impacts of power plants and sustainability of the watershed [3].

Fossil fuel power plants not only require a huge amount of water, but also emit 28% of the 2016 U.S. greenhouse gas emissions [4], 67% of the 2014 U.S. SO_2 emissions, and 12% of the 2014 U.S. NO_x emissions [5]. Ecosystem services, such as climate change regulation and air quality regulation, could play an important role in mitigating these pollutants and emissions. The ecosystem provides many essential goods and services to society and for our well-being. Ecosystem goods include water and fossil resources that our society has been extensively utilizing. Ecosystem services include air and water quality regulation and carbon sequestration by soil and vegetation. Therefore, in addition to the conventional energy-water nexus concept, we need to expand the system boundary to include the role of ecosystems. The framework of Techno-Ecological Synergy (TES) has been developed to account for the role of ecosystems in engineering and other human activities [6, 7]. In this framework, the demand for ecosystem services imposed by human activities, which correspond to the emissions and resource use, must not exceed the capacity of the corresponding ecosystem to supply the demanded goods and services. This condition needs to be satisfied to claim environmental

sustainability of any activity. For example, for environmental sustainability of a power plant in a watershed, the amount of water consumed by the power plant should be smaller than the amount of renewable water available to the plant from the watershed. Otherwise, power plants will likely fail at some point because water resource will become scarce.

In the watershed where power plants are located, other activities, such as residential, industrial, and farming, also share the supply of ecosystem goods and services with electricity generation activity. Also, to address watershed-scale sustainability, the demand for ecosystem services from all activities in a watershed needs to be considered. This raises the need for a holistic assessment to investigate watershed sustainability. In such an analysis, the trade-offs between multiple objectives, such as water quality, water quantity, net electricity generation, climate change, and air quality objectives, could be identified as well.

In this work, we employ a holistic analysis approach to investigate the energy-water-CO_2 nexus for thermoelectric power plants, with specific focus on the Muskingum River Watershed (MRW) in Ohio in the United States. In 2014, two coal-fired power plants and three NG-fired power plants were located in the MRW. The year 2014 is selected because of data availability from a variety of online sources and reports. The holistic analysis boundary includes thermoelectric power generation, mining, residential, commercial, industrial, agricultural, transportation and wastewater treatment activities.

To suggest a better recommendation for sustainable watershed management, various alternatives for both technological and agroecological activities are considered. Technological alternatives include fuel mining and cooling technology options for power generation, CO_2 conversion options, and renewable power generation options. Agroecological alternatives include tillage practice options and land use change options. Scenarios for each alternative are analyzed to understand the trade-offs between multiple flows.

CO_2 flows are affected by both technological and agroecological alternatives in various ways. Technological alternatives mainly aim to reduce CO_2 emissions while agroecological alternatives improve carbon sequestration in soil and vegetation. Broader implications in terms of CO_2 management are addressed through the holistic analysis of watershed activities.

The goal of this work consists of three parts. First, we identify ecological overshoots for activities in the MRW. Second, we investigate various alternative scenarios to understand the trade-offs between energy, water, and CO_2 flows. Third, we suggest better watershed management solutions that could be "win-win" in terms of multiple objectives for watershed sustainability.

2   Methodology

In this section, we describe the characteristics of various watershed activities that are included in this holistic assessment study. Data collection is a challenging task for such a holistic assessment because we need to rely on multiple data sources that often have different spatial and temporal data resolutions. Thus, it is important to keep spatial and temporal consistency between data. In this study, watershed-scale data for the year 2014 is preferred because most data are available for this year. The watershed boundary is determined by the Hydrologic Unit Code (HUC) system that assigns a unique HUC code to each watershed [8]. Each HUC region is defined by distinct hydrologic features, such as rivers, lakes,
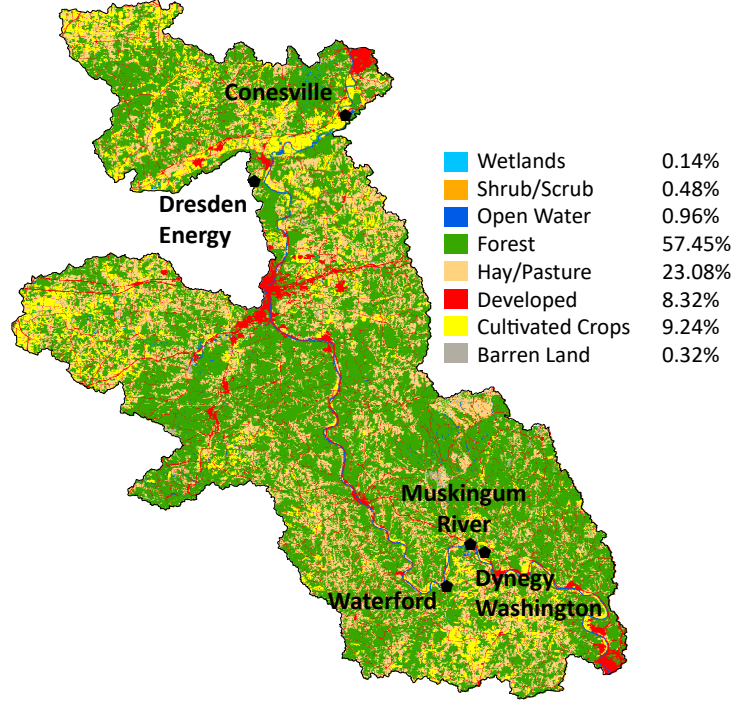
Figure 1: Land use and land cover features in the Muskingum River Watershed (HUC8: 05000405) in Ohio. Five thermoelectric power plants (⬟) were located in the MRW in 2014.

and drainage basins. The Muskingum River Watershed (MRW) studied in this work corresponds to a region where 8-digits of HUC (HUC8) is assigned as 05040004. The MRW is located in southeast Ohio. Water flows from the MRW drains into the Muskingum River which eventually flows into the Ohio River. Figure 1 shows land use and land cover features in the MRW.

If any data are not available for HUC8 spatial resolution, the data is allocated to HUC8 based on the ratio of population or area. For example, data for air pollutants is available for US counties [5], which do not match HUC spatial resolution. The MRW includes eight counties in Ohio: Coshocton, Licking, Knox, Muskingum, Perry, Morgan, Washington, and Noble. The county-level data are then allocated to the MRW based on the ratio of HUC8 area to eight counties' area. For other data, such as residential and commercial activity data, that are more dependent on population rather than area, the allocation is performed based on the population. Table 2 summarizes data inventories, data sources, and spatial data resolution for this work. When life cycle inventory databases, such as GREET [9] and USLCI [10], are used to obtain data, only on-site data are collected since the scope of this study is limited to the watershed scale. Figure 2 represents the scope of this study that includes various watershed activities and resource, waste, and ecosystem flows. In the following sections, we provide brief descriptions of each watershed activity.

3

Activity	Environmental & Material Flow	Data Source	Spatial Resolution
Theremoelectric	GHG emissions	EPA eGRID [11]	Facility
	Air pollutants	EPA NEI [5]	County
	Water pollutants	EPA NPDES [12]	Facility
	Thermal water pollution	EIA-923 [13]	Facility
	Water withdrawal	EIA-923 [13]	Facility
	Water consumption	EIA-923 [13]	Facility
	Natural gas use	EIA-923 [13]	Facility
	Electricity use	EIA-923 [13]	Facility
	Electricity generation	EIA-923 [13]	Facility
Mining	GHG emissions	GREET [9]	U.S. average
	Air pollutants	EPA NEI [5]	County
	Water pollutants	NETL [14,15]	Appalachia average
	Water withdrawal	USGS [16]	Ohio
	Water consumption	GREET [9]	U.S. average
	Natural gas use	EIA [17]	Ohio
	Electricity use	USLCI [10]	U.S. average
Agricultural & Other Activities (Residential, Commercial, Industrial, Transportation, Wastewater treatment)	GHG emissions	EPA GHGRP [11], EPA NEI [5]	Facility, County
	Air pollutants	EPA NEI [5]	County
	Water pollutants	(Agricultural) SWAT [18], (Other activities) EPA [19]	HUC12 HUC4
	Water withdrawal	EnviroAtlas [20]	HUC8
	Water consumption	USGS [16]	Ohio
	Natural gas use	EIA [17]	Ohio
	Electricity use	EIA [21]	Ohio
Ecosystem Supplies	Carbon sequestration	i-Tree Landscape [22]	HUC8
	Air quality regulation	i-Tree Landscape [22]	HUC8
	Water quality regulation	[23,24]	Average
	Water provision	SWAT [18]	HUC12
	Natural gas provision	[25]	Global

Table 1: Data sources for activities and environmental interventions in the MRW. If the spatial resolution of data is larger than HUC8 scale, the data is allocated to the HUC8 scale based on the ratio of population or area.
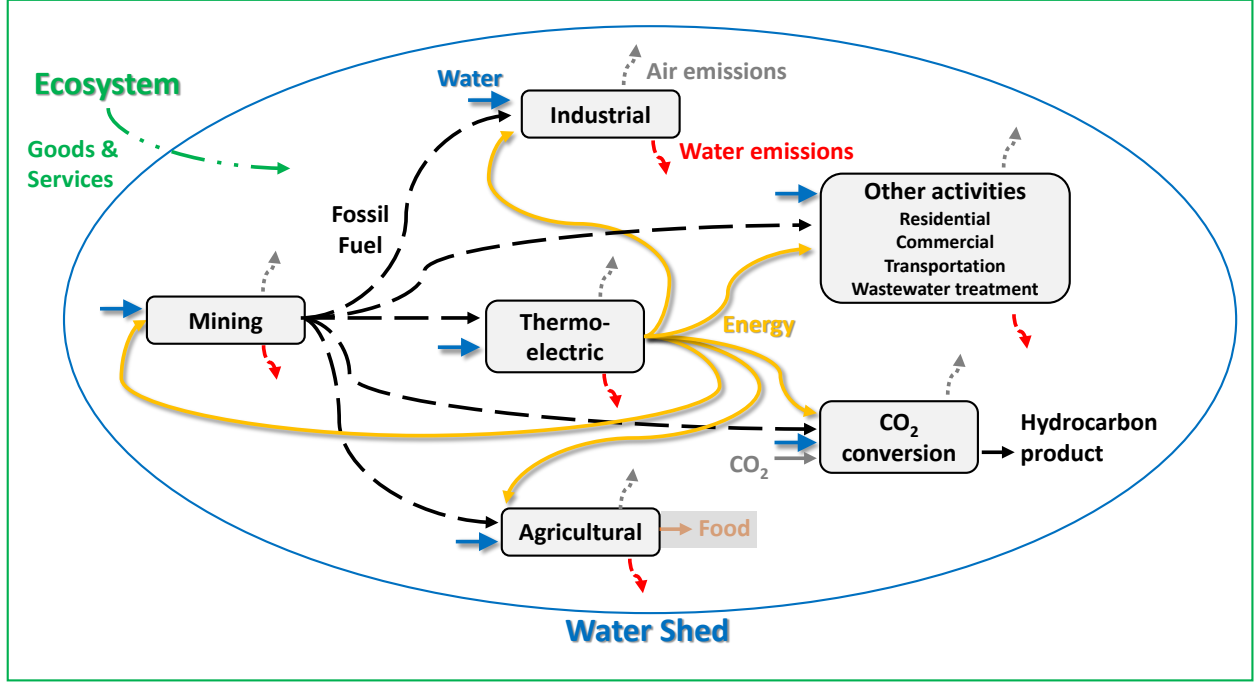
Figure 2: Scope of this study that includes various watershed activities and resource, waste, and ecosystem flows. Food production flow from agricultural activity is excluded from this study.

2.1 Thermoelectric power generation

In the MRW, there are two coal-fired steam turbine power plants and three natural gas-fired combined cycle (NGCC) power plants, as shown in Fig. 1. The Muskingum River Power Plant was retired in 2015 due to environmental regulations [26]. However, since our study is for 2014, we assume that the Muskingum River Power Plant is still operating to keep the temporal consistency of data.

In terms of the power generation technology of thermoelectric power plants, 99% of coal-fired power plants in the U.S. employ steam turbine boilers, while 84% of NG-fired power plants in the U.S. employ combined cycle boilers [9]. Since five power plants in the MRW are also operated by using these generation technologies, we only consider these two types of power generation technologies in this study.

Fossil power generation is responsible for about 45% of freshwater withdrawals in the U.S. [1]. Most water withdrawn is used for the cooling of boilers. Depending on which cooling methods are employed in the power plant, water and energy requirements are varied. Once-through cooling technology, also known as the open-loop cooling system, withdraws a massive amount of water but returns most of it at a warmer temperature to the watershed. The once-through cooling system has been mainly installed in power plants in the eastern U.S. On the other hand, recirculating cooling technology, also known as the closed-loop cooling system and cooling tower, withdraws only a fraction of water that systems require, recirculates water, but consumes most of it through evaporation from cooling tower. Therefore, recirculating cooling technology has higher water consumption than once-through cooling technology, even

though its amount of water withdrawn is significantly lower. Also, it has lower electricity generation efficiency and is more expensive than once-through cooling technology [27]. The recirculating cooling system is widespread in the western U.S. In contrast to those wet cooling methods, the dry cooling technology uses no water, but requires more energy and higher capital and operation costs, and results in lower generation efficiency than wet cooling technologies. The lower generation efficiency means that more fossil resources are required to generate electricity, and thus, it will increase the impacts from upstream processes, such as mining and transportation of fossil fuels.

Among the five power plants in the MRW, only one coal-fired plant, the Muskingum River Power Plant, employs once-through cooling technology and other four plants employ the recirculating cooling technology. In this study, three cooling technologies (once-through, recirculating, and dry cooling) are considered as technological alternatives for thermoelectric activity. It is reported that 0.3–1% and 2–4% reductions in generation efficiency are expected for thermoelectric power plants in Texas if the once-through cooling system is converted to recirculating and dry cooling systems, respectively [28]. Also, 0.60–0.63 cents/kWh of cost is required for the plant operator to retrofit a recirculating cooling system to a dry cooling system.

2.2 Mining of fossil resources

In 2017, coal and natural gas accounted for 34% and 26% of energy sources that were used to generate electricity in the U.S., respectively [29]. Depending on which fossil resources are exploited, total environmental interventions from fossil power generation are hugely varied. This is mainly attributed to the fact that each fossil resource contains different chemical compositions. Furthermore, in the case of NG extraction, the hydraulic fracturing of shale gas requires substantial water resources compared to the conventional NG extraction [3, 30, 31]. According to the previous study, however, the amount of water withdrawn for the fracking is much smaller than the amount of cooling water for power generation [30]. Fracking also contaminates water resources due to wastewater discharged from shale wells [32, 33].

The transportation of fossil fuels from mining sites to the power plants is considered as well. While coal is generally transported by truck and railroad, NG is primarily transported by pipeline. The leakage of gas from the pipeline transportation is also considered.

2.3 Farming

Figure 1 shows land use and land cover in the MRW. Total area for agricultural land use is approximately 3.8×10^8 m^2. The MRW is not a region where agricultural production dominates. However, nutrient runoff from farming activity can be varied depending on which farming practices are performed. Hence, agricultural practice management is crucial to prevent deteriorating water quality. According to the previous findings, farming activity in the river basin that includes MRW contributes significantly to total nitrogen (TN) and total phosphorus (TP) loads in the river basin [18].

Tillage practices are performed to prepare the soil for crop production. However, it damages the soil structure and increases nutrient runoffs. Currently, four different tillage

practices are employed in the MRW. 57.0% of the agricultural land area performs no-till practice. 22.9%, 20.0%, and 0.11% carry out conservation (chisel plow), reduced (tandem-disc plow), and intensive (moldboard plow) tillage practices. The conservation tillage practice is defined as tillage that has more than 30% of crop residues on the soil. The reduced and intensive tillage practices have 15–30% and less than 15% of crop residues that remain on the soil, respectively. The increased mixing efficiency leads to low crop residues, requires many fertilizer inputs, and increases the risk of soil erosion.

No-till practice helps reduce soil erosion and nutrient runoffs since more crop residue remains in the soil, and thus, fewer fertilizers need to be applied [34]. Also, no-till practice is economically cheaper than tillage practices due to the reduced labor and fuel requirements. The long-term crop yield may be increased as well due to improved soil fertility. However, the food production flow is excluded from this study to focus on the nexus of energy and water flows. Differences in other interventions, such as air emissions and resource uses, between tillage practices are also taken account of, even though their contribution is relatively negligible compared to thermoelectric activity [10, 35].

2.4   Miscellaneous activities

Although mining, thermoelectric, and agricultural activities account for most of the water use and pollutant emissions, other activities also consume water and energy and release emissions. Therefore, for the comprehensive analysis of the energy-water-CO_2 nexus in the MRW, various activities that include residential, commercial, industrial, transportation, and wastewater treatment, are included in the analysis. This comprehensiveness of the analysis boundary is particularly important when the TES framework is applied. Since ecosystem supplies, such as water provisioning, account for the entire amounts of supplies from the MRW, their associated ecosystem demands, such as water consumption, also need to be the total demands from all activities in the MRW.

2.5   Supply of ecosystem services

Traditional sustainability assessment approaches, such as conventional life cycle assessment (LCA), account for environmental impacts from activities. The impacts include emissions and resource use. These traditional methods quantify only relative sustainability to answer the question: whose impacts are smaller than others? To claim absolute sustainability, however, we need to address how the surrounding ecosystem offsets those impacts. The TES framework accounts for the supply and demand of specific ecosystem goods and services and introduces a TES sustainability metric: $V_k = (S_k - D_k)/D_k$ [6, 7]. The ecosystem service demand (D) corresponds to environmental flows, such as air emissions and water consumption. The ecosystem service supply (S) corresponds to the provisioning of ecosystem goods and services, such as air quality regulation service and water resource provision. The TES metric V_k is calculated for each type of ecosystem good and service (k). A positive V_k indicates that impacts do not overshoot the capacity of ecosystem supplies, which means the system is sustainable in terms of k ecosystem goods and services.

Forest ecosystems and tree canopies provide carbon sequestration and air quality regulation services. Wetlands regulate water quality by removing excessive nutrient runoffs,

although only 0.14% of land area in the MRW is wetlands as shown in Fig. 1. With respect to ecosystem goods, such as water and fossil resource provisioning, only the renewable portion can be included as the supply of such ecosystem goods. To assess water provisioning in the MRW, for example, various factors about the water cycle, such as precipitation, evapotranspiration from canopy and soil, infiltration into the soil, and surface/subsurface runoffs, need to be considered. In this study, the Soil and Water Assessment Tool (SWAT) model is used to calculate the available amount of water in the MRW [18].

Fossil resources are formed from organic matter in the earth through anaerobic decomposition over very long periods of time. With respect to the natural gas supply from the ecosystem, only renewable NG should be considered as the ecosystem supply. However, since the formation rate of NG is significantly slower than the NG consumption rate, the TES metric for NG (V_{NG}) is very close to negative one (-1) regardless of any scenarios. In this work, therefore, we consider the other case where $2\,°C$ of global warming since the pre-industrial period is allowed for exploiting accumulated NG [25]. According to the Intergovernmental Panel on Climate Change (IPCC), the rise in global temperature must be limited to $2\,°C$ above pre-industrial levels in order to avoid disastrous consequences of climate change [25]. The IPCC has calculated the carbon budget that represents the amounts of global CO_2 emissions for keeping global warming under $2\,°C$. The remaining budget for greenhouse gas emissions is estimated to be 275 GtC [36]. Since 22% of GHG emissions are attributed to the use of NG [29], 60 GtC of the budget can be allocated to the GHG emissions from NG use. This budget is further allocated to the NG use in the MRW based on the ratio of NG consumption in the MRW to global NG consumption [37]. The resulting budget is the amount of NG supply in the MRW that allows $2\,°C$ of global warming.

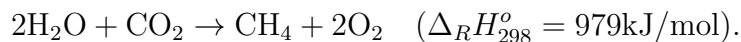## 2.6 Potential CO_2 conversion technologies

As a way of mitigating CO_2 emissions, extensive research is being conducted on technologies for converting CO_2 into a variety of hydrocarbon products [38–41]. In this work, three CO_2 conversion technologies are selected as technological alternative options to improve watershed sustainability. First, methane (CH_4) is produced from carbon dioxide and hydrogen through Sabatier exothermic reaction as follows:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (\Delta_R H^o_{298} = -165 \text{kJ/mol}).$$

CO_2 feedstocks are assumed to be captured from thermoelectric power plants. To provide hydrogen for hydrocarbon products, it is assumed that a water resource is utilized through an electrolysis process as follows:

$$H_2O \rightarrow H_2 + 1/2O_2 \quad (\Delta_R H^o_{298} = 286 \text{kJ/mol}).$$
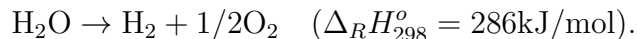
Therefore, the overall reaction is:

$$2H_2O + CO_2 \rightarrow CH_4 + 2O_2 \quad (\Delta_R H^o_{298} = 979 \text{kJ/mol}).$$

The converted CH_4 product is assumed to displace natural gas in the MRW since most of the NG composition is CH_4. Therefore, displacement credits of all kinds of avoided emissions and resource uses are given to CO_2 conversion technologies.

8

CO_2 is also used to produce synthetic gas through the reverse water-gas shift reaction as shown below:

$$CO_2 + H_2 \rightarrow CO + H_2O \quad (\Delta_R H^o_{298} = 41\text{kJ/mol}).$$

If syngas that has a ratio of H_2 to CO of 2:1 is required, hydrogen is obtained from the electrolysis of water shown above. Also, formic acid is synthesized from the hydrogenation of CO_2 as follows:

$$CO_2 + H_2 \rightarrow HCOOH \quad (\Delta_R H^o_{298} = -31.5\text{kJ/mol}).$$
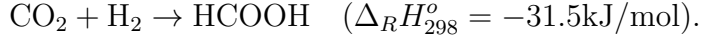
Similarly with the displacement approach for CH_4, it is assumed that CO_2-converted syngas and formic acid displace each of the products from conventional processes. Syngas is produced from conventional coal gasification process [42]. 69% of formic acid is synthesized from methyl formate and the rest of it is produced from butane [43].

Since the CO_2 conversion technologies described above still have not been fully developed for commercialization, stoichiometric reactions are assumed for all CO_2 conversion scenarios for the simplicity of analysis. The energy demand for CO_2 conversion is estimated using the standard enthalpy of each conversion reaction ($\Delta_R H^o_{298}$). Numerous experimental data are available from literature [41, 44]. However, those data vary substantially depending on process configurations, such as the use of a specific catalyst. For example, one report employed 30 bar of CO_2 pressure for converting CO_2 to formic acid [45], while the other one employed 120 bar of CO_2 pressure [46]. This makes the analysis challenging since we cannot just randomly select one technology for the comparison between different conversion scenarios (i.e., CO_2 conversion to methane, syngas, and formic acid). For a more accurate analysis, process data for CO_2 capture using monoethanolamine (MEA) is included in the analysis [47] since the CO_2 capture process is common for all conversion technologies. It is assumed that MEA is produced from outside MRW. With respect to the energy demand for CO_2 compression, we assume that 30 bar of CO_2 pressure is required for all conversion technologies since many formic acid production technologies from CO_2 employed 30 bar of CO_2 pressure [41, 44].

The overall CO_2 conversion that includes the electrolysis of water is not only water-intensive but also energy-intensive. Thus, significant amounts of water and energy resources are demanded. This could make CO_2 conversion options infeasible by shifting impacts of GHG emissions to the impacts of energy and water consumption since the interventions from power generation are also increased.

2.7 Potential renewable electricity sources

To lessen the interventions from the increased demand for electricity for CO_2 conversion technologies, renewable electricity sources are considered to provide electricity for CO_2 capture, compression, and conversion by displacing conventional, thermoelectric power generation [39]. In this study, solar and wind power sources are considered to replace fossil fuel sources in the MRW. These renewable power generation technologies do not consume as much water as thermoelectric power generation [48]. Solar power generation includes two technologies: photovoltaics (PVs) and concentrated solar panels (CSPs). 57% of solar power generation in the U.S. uses PVs and the rest of it employs CSPs [49]. In this study, it is

assumed that the national average solar power generation technologies are employed. While the water consumption for PVs is negligible, the solar power generation using CSPs requires similar water consumption as thermoelectric power generation due to the cooling of panels and steam turbines. In terms of wind power generation, its water consumption is insignificant since it does not require cooling.

In the same manner of the displacement approach for CO_2 conversion technologies, it is assumed that various environmental interventions that are associated with thermoelectric power generation and its upstream activities, such as mining, can be avoided since electricity is produced from renewable power generation. Also, data for solar and wind power generation potentials in the MRW are investigated and considered as constraints that represent the maximum amount of renewable electricity generated from the available land area in the MRW [20].

2.8 Potential Land use changes

The MRW has 0.32% of barren land area as shown in Fig. 1. This corresponds to approximately 13×10^6 m^2 of land area. In this study, two land use change scenarios for the available land are investigated as follows: Reforestation and wetland construction. If the available land is reforested, supplies of various ecosystem goods and services are increased. The supplies of carbon sequestration and air quality regulation services are enhanced since these services are provided from vegetation in a forest [50]. Nutrient loads in streams are reduced due to the reduction in runoff [51]. With respect to water provision, there is a debate on whether reforestation helps improve water supply in watersheds. A majority of reports claim that water availability is reduced in a short period of time due to the reforestation and is recovered in a considerable time because of the improved soil infiltration capacity and the increased groundwater levels [52].

In the MRW, wetlands occupy only a very small portion of the landscape as shown in Fig. 1. Newly-constructed wetlands can improve the supply of water quality regulation service. Previous reports have discussed how much nutrient runoff could be reduced by constructed wetlands [23, 24]. In this study, we calculate the increased amounts of nitrogen and phosphorus removals due to the constructed wetlands in the available land.

3 Principal Findings and Result

3.1 Base case analysis

To investigate the base case condition of activities in the MRW, various environmental interventions from each activity are plotted in Fig. 3. Thermoelectric activity shows the most dominant contribution to many environmental interventions. Thermoelectric power plants are responsible for 69.6% of water consumption, 82.4% of GHG emissions, 68.4% of NO_X emissions, and 97.1% of SO_2 emissions in the MRW. These results align well with the U.S national average [1, 4, 5], although the contribution from thermoelectric activity in the MRW to those interventions is much larger than the national average. This is because the MRW is an intensive area in terms of thermoelectric activity. The MRW is a region where

17.4% of Ohio's electricity is generated [13], although the population in the MRW is only 1.1% of the state's population. For some air emissions, such as PM_{10} and CO, transportation activity is the dominant contributor. Also, most of the water nutrient emissions, such as total N and P loads, are attributed to agricultural activity. For electricity consumption, industrial activity is the most dominant activity.

Conventional sustainability assessment approaches only account for environmental interventions, such as emissions and resource uses, which correspond to ecosystem demands. As described in Section 2.5, however, all ecosystem demands need to be compared with their corresponding ecosystem supplies in assessing the sustainability of watershed activities. Base case analysis results in terms of the demands and supplies of electricity and ecosystem goods and services are shown in Fig. 3. The TES sustainability metrics are calculated for each ecosystem good and service and are shown in Fig. 4.

As shown in Fig. 3, net electricity generation in the MRW is calculated to be 95.9 TJ/day. Most ecosystem supplies are smaller than their corresponding ecosystem demands. Only the water demand from activities in the MRW does not exceed the water supply from the ecosystem in the MRW. This indicates that the MRW is not a water-scarce region but has a scarcity of other ecosystem services. As shown in Fig. 3, the amount of water withdrawn is significantly large, but it is not considered as the ecosystem demand for water provision since most of the withdrawn water returns to the water body. Rather, the amount of water consumption is considered as the ecosystem demand. In terms of the natural gas supply, approximately 2.5×10^6 m^3/day of accumulated NG is considered as the supply of NG by allowing for 2 °C of global warming as described in Section 2.5. The TES metric for NG is then calculated for this adjusted NG supply.

To identify ecological overshoots for activities in the MRW, various TES metrics are calculated for the base case. As shown in Fig. 4, most TES metrics are negative, which indicates that environmental interventions overshoot the capacity of ecosystems in the MRW. Most of those interventions are attributed to the thermoelectric activity, as shown in Fig. 3. Activities in the MRW are environmentally sustainable only with respect to water consumption since the TES metric for water is positive.

3.2   Technological alternatives

To address the nexus of multiple flows in the analysis, multiple objectives that represent these flows need to be considered. In this work, the following objectives are included: TES metrics for greenhouse gases and air pollutants (V_{CO_2}, V_{NO_X}, V_{SO_2}, $V_{PM_{2.5}}$, $V_{PM_{10}}$, and V_{CO}), TES metrics for water nutrient runoffs (V_{TN} and V_{TP}), TES metrics for ecosystem goods (V_{H_2O} and V_{NG}), net electricity generation, marginal cost for each alternative, and thermal water pollution from power plants. Various scenarios about technological alternatives are examined to improve the sustainability of activities in the MRW. As a functional unit for the comparison between alternatives, power plants in the MRW are assumed to generate 230 TJ/day of electricity regardless of which alternatives are adopted. This corresponds to the amount of electricity generated from the five fossil plants in the MRW in 2014. The TES metrics are plotted in radar diagrams as shown in Fig. 5. Larger values are preferred for each TES metric objective.
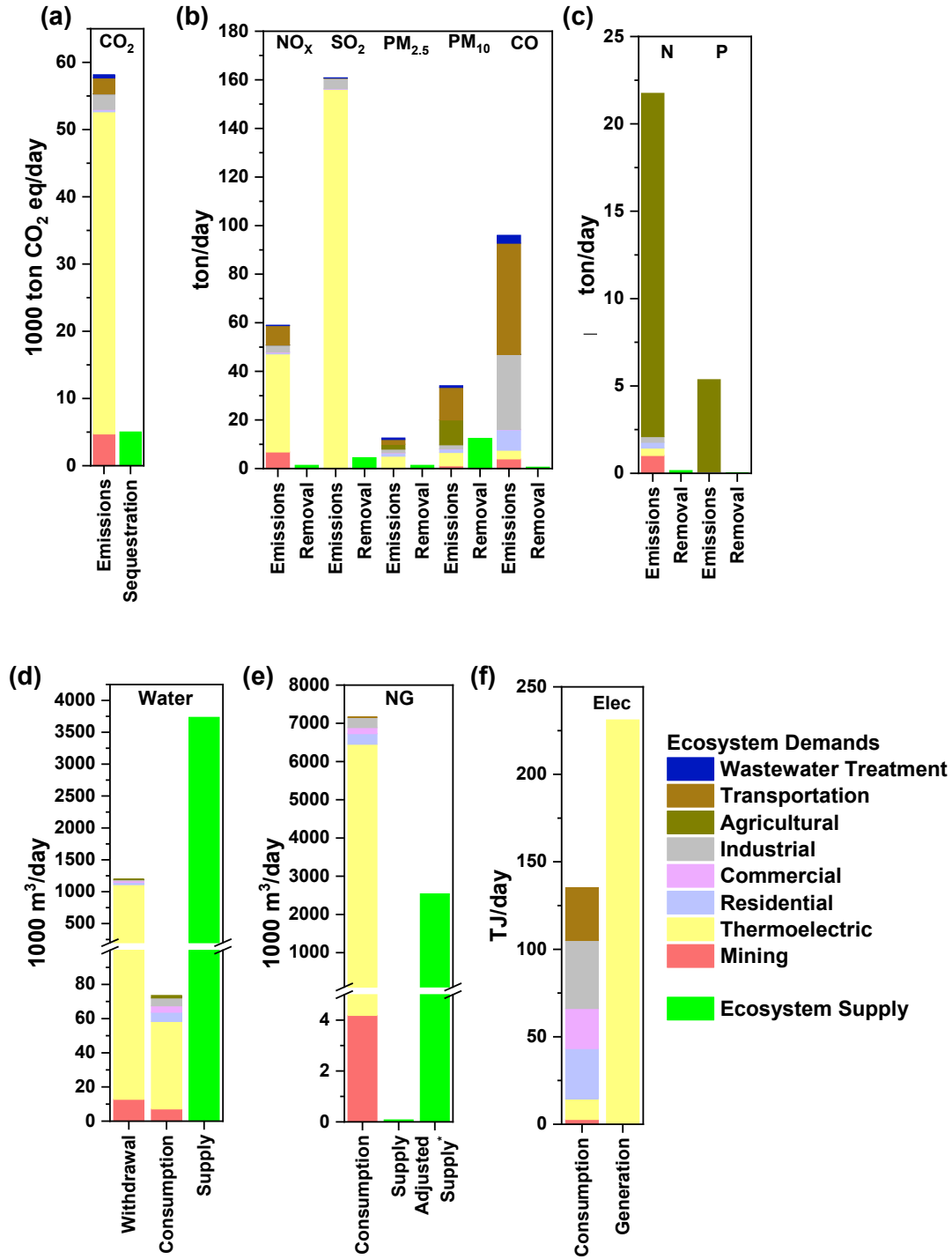
Figure 3: Base case analysis results in terms of the demands and supplies of electricity and ecosystem goods and services. (a) Carbon sequestration. (b) Air quality regulation. (c) Water quality regulation. (d) Water provisioning. (e) NG provisioning. (f) Electricity (* Adjusted NG supply includes the amount of accumulated NG by allowing for $2\,^{\circ}\mathrm{C}$ global warming since the pre-industrial period.)
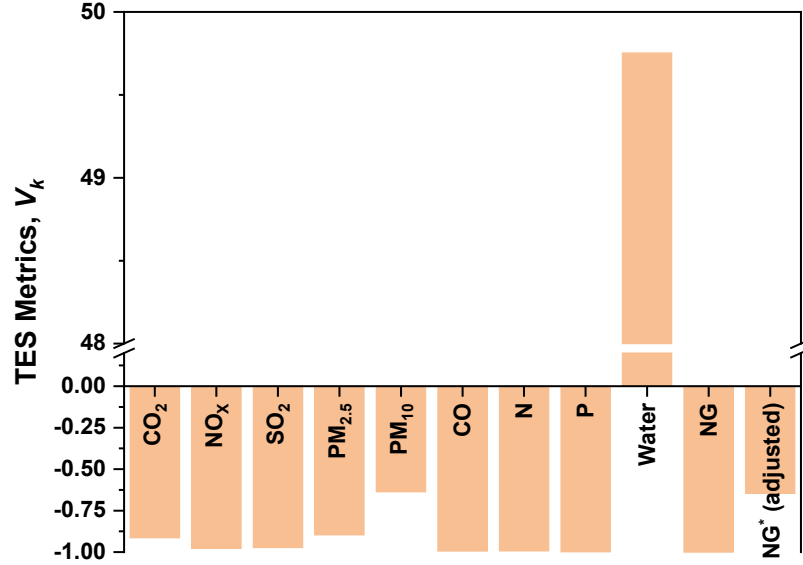
Figure 4: TES sustainability metrics calculated for each ecosystem good and service.

3.2.1 Technology options for fuel and power generation

Figure 5(a) shows various sustainability indicators for the scenario where one type of fuel and electricity generation technology are adopted for all five fossil power plants in the MRW. Three kinds of fuel and generation technology options include coal-fired steam turbine power plants (Coal ST), conventional NG-fired combined cycle power plants (Conv NG CC), and shale NG-fired combined cycle power plants (Shale NG CC). All options are assumed to employ recirculating cooling technology (RE).

For most indicators except V_{NG^*}, the coal-fired steam turbine option is the worst among other fuel and generation technology options. This is not only because burning coal causes more air emissions than burning NG but also because coal-fired steam turbine plants have lower generation efficiency than the NGCC plants. In particular, V_{SO_2} indicator can be improved significantly by employing NGCC plants since NGCC plants have very negligible SO_2 emissions compared to coal-fired plants. Also, coal-fired steam turbine plants consume more water than NGCC plants per kWh of electricity generated. Moreover, coal mining and coal-fired steam turbine plants require more electricity than NG extraction and NGCC plants. Only the V_{NG^*} indicator shows that the coal-fired steam turbine option is better than two NG options because coal is selected to be burned as fuel instead of NG. In terms of the comparison between conventional NG and shale NG options, there are very minor differences. For instance, V_{H_2O} value for the conventional NG option is only 4.5% larger than the shale gas option. This is because power generation technology is the same between these two NG options and the impacts of mining activity is negligible compared to the impacts
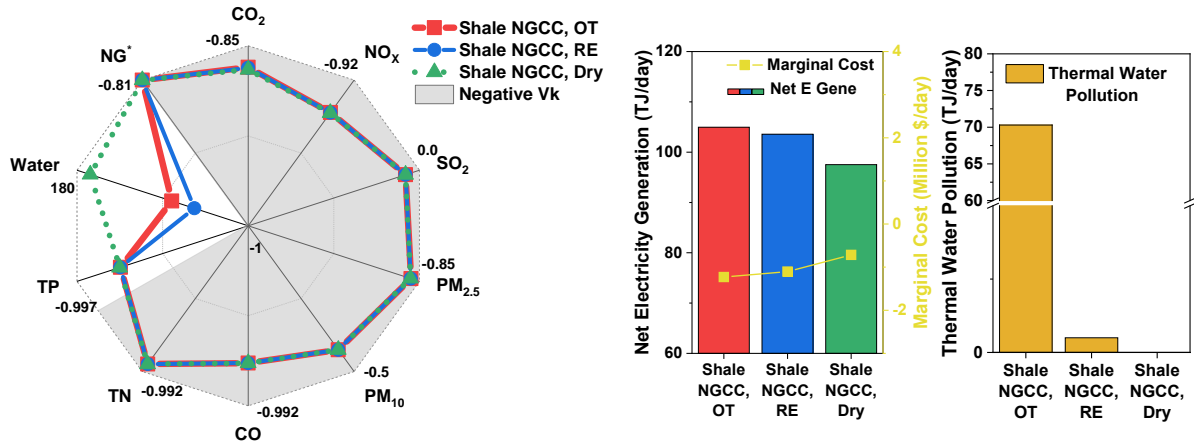
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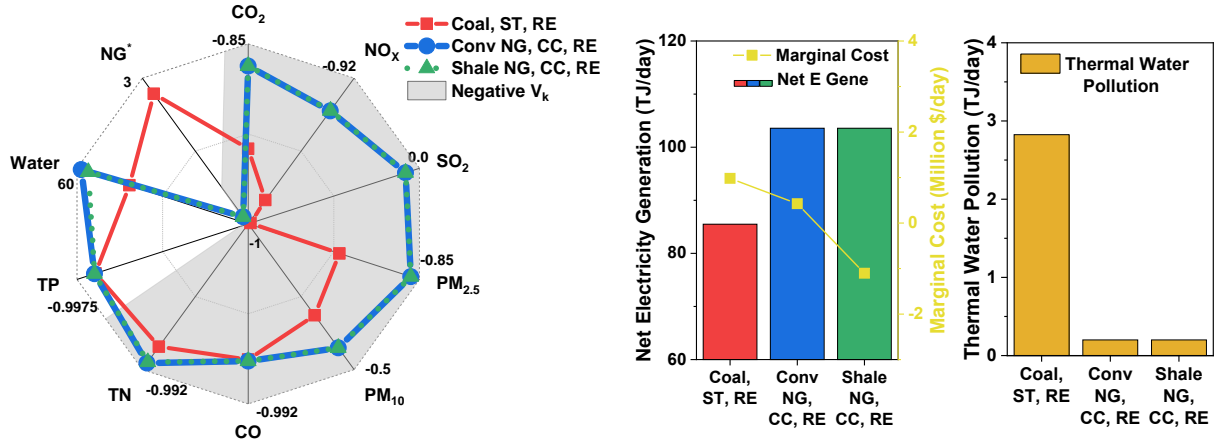
(b)

Figure 5: Sustainability indicators for technological alternatives. TES metrics are plotted in radar diagrams. (a) Fuel and electricity generation technology options. (b) Cooling technology options.

14

of the thermoelectric activity, which is the most dominant activity for most interventions. Moreover, the slight decrease in V_{H_2O} indicator for the shale option compared to the conventional NG option does not imply a meaningful difference since water resource in the MRW is abundant. Rather, we should take account of the availability of NG reserves because the production rate of shale NG in Ohio is expected to keep increasing [53]. Also, the production cost for shale NG is cheaper than conventional NG [54].

3.2.2   Cooling technology options

Two types of wet cooling technologies, once-through cooling (OT) and recirculating cooling (RE), and dry cooling technology are compared for shale NG-fired combined cycle power plants as shown in Fig. 5(b). For V_{H_2O} indicator, the dry cooling option is better than wet cooling options since it does not require the use of water. However, since dry cooling is 1–3% less efficient than wet cooling methods [28], dry cooling requires more electricity and fuel inputs to produce the same amount of electricity. Accordingly, net electricity generation of dry cooling is smaller than that of the wet cooling options. Also, dry cooling technology is much more expensive than wet cooling technologies [28].

The once-through cooling option shows a larger V_{H_2O} value than the recirculating cooling option. However, once-through cooling technology withdraws a huge amount of water and returns most of it at a warmer temperature, which results in significant thermal water pollution. According to the records for the existing power plants in the MRW, coal-fired steam turbine plant with once-through cooling system causes 19 times larger thermal water pollution than that with recirculating cooling system [13]. Therefore, once-through cooling technology is not advisable.

3.2.3   CO$_2$ conversion technology options

Although V_{CO_2} indicator can be improved by employing NG instead of coal, its TES metric value is still negative ($V_{CO_2} = -0.87$). Figure 6(a) exhibits the results for several CO$_2$ conversion technology scenarios to mitigate CO$_2$ emissions in the MRW. In this work, it is assumed that 1,000 t/day of CO$_2$ are converted to CH$_4$, synthetic gas, and formic acid. The results exhibit the increase in V_{CO_2} indicator and the reduction in net electricity generation for CO$_2$ conversion options compared to the base case.

Table 3.2.3 shows the interventions from CO$_2$ conversion processes and displacement credits from conventional processes. The CO$_2$ conversion processes include CO$_2$ capture, compression, and conversion to products. Total CO$_2$ emissions from the conversion processes are -745 t/day when 1,000 t/day of CO$_2$ is captured and converted to products since approximately 255 t/day of CO$_2$ is emitted from the CO$_2$ capture process. The conventional coal gasification process to produce syngas has high greenhouse gas emissions. Since these GHG emissions can be avoided as a displacement credit for CO$_2$ conversion to syngas, the syngas option shows the best V_{CO_2} value among the conversion options. On the other hand, in terms of net electricity generation, the formic acid option shows a higher value than the other two conversion options. This is because the total electricity requirement for CO$_2$ conversion process to formic acid is relatively smaller than that for other conversion processes. Also, formic acid option is cheaper than other conversion options.
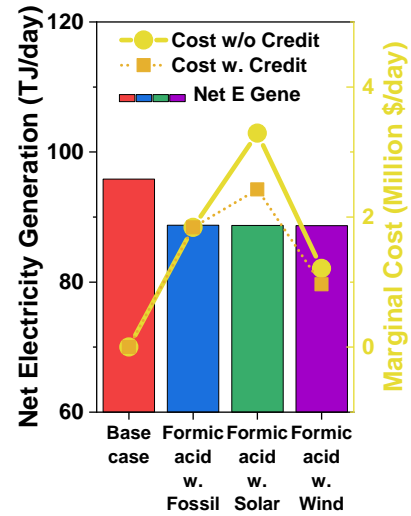
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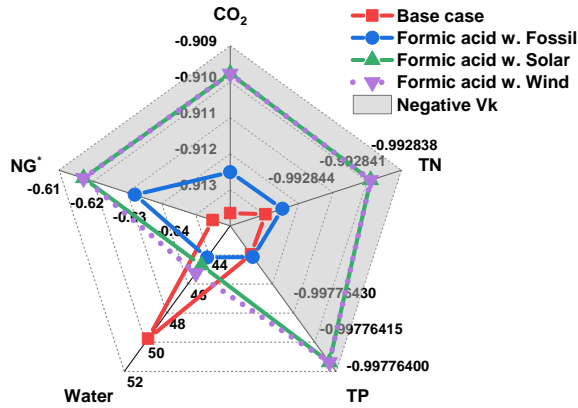**(a)**
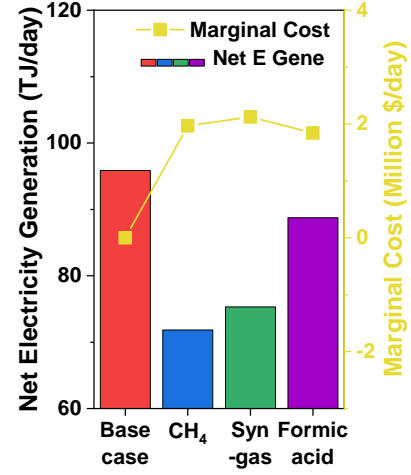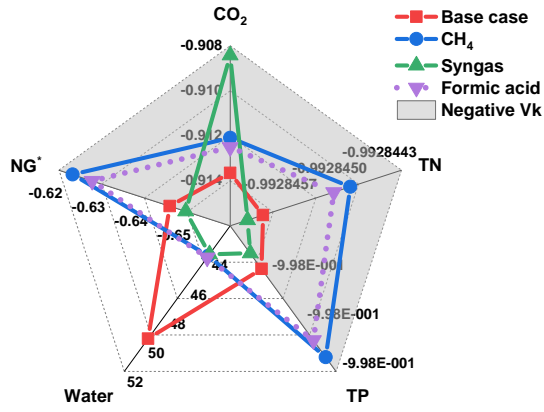
(b)

Figure 6: Sustainability indicators for technological alternatives. TES metrics are plotted in radar diagrams. (a) CO_2 conversion technology options. (b) Renewable power generation technology options

Conversion alternative	Conversion to CH_4			Conversion to synthetic gas			Conversion to formic acid		
	Electricity use (TJ/day)	Water use (m³/day)	CO_2 emissions (t/day)	Electricity use (TJ/day)	Water use (m³/day)	CO_2 emissions (t/day)	Electricity use (TJ/day)	Water use (m³/day)	CO_2 emissions (t/day)
Interventions from conversion process[1]	24.10	9,486	-745	22.28	9,486	-745	7.64	9,076	-745
Displacement credits from conventional process	-0.08	-199	-289	-1.73	0	-2,576	-0.54	-1	-13

Table 2: Interventions from CO_2 conversion processes and displacement credits from conventional processes. [1]CO_2 conversion includes CO_2 capture, compression, and conversion to products. Stoichiometric reactions are assumed for CO_2 conversion processes.

In this work, hydrogen is assumed to be provided from water resource. As shown in Fig. 6(a), V_{H_2O} values are decreased when CO_2 is captured and converted to the products. This is because a CO_2 capture system increases water consumption for cooling [55]. Even though CO_2 conversion scenarios intensify water consumption, however, it does not affect the sustainability of watershed because the MRW is not a water-scarce region as shown in Fig. 4. V_{H_2O} values for CO_2 conversion scenarios are approximately 1.20, which is still positive.

As the results show, in choosing the best option between CO_2 conversion alternatives, it is crucial to consider the impacts that are avoided from conventional processes as well as technological advances of CO_2 conversion processes because the displacement credits from the conventional processes can be significant. Also, the results indicate that the increased water consumption from the CO_2 conversion options is not of much concern since the MRW has abundant renewable water to offset total water consumption. This emphasizes the needs for holistic assessment and TES assessment in addressing the sustainability of watershed.

Using CO_2 as a source of carbon is an energy-intensive process. In most cases, therefore, CO_2 conversion technologies are economically expensive. According to the study, the net present value of CO_2 conversion to formic acid is negative at least for 10 years due to the capital investment cost [56]. However, the profitability of CO_2 conversion process to formic acid can be enhanced if the cost of consumable chemicals is reduced and the life time of catalyst is increased. Also, if the carbon price is included, the additional revenues can be earned through the CO_2 conversion process.

The limitation of market capacity for formic acid from CO_2 needs to be considered, especially if the cost for converting CO_2 to formic acid can be cheaper than that for conventional formic acid. Formic acid is generally used as a preservative and antibacterial agent in animal feed. The global production capacity of formic acid in 2009 was roughly 720,000 t/y [57]. 1,000 t/day of CO_2 conversion to formic acid in this study corresponds to more than half of the worldwide formic acid production. However, the demand for formic acid could be increased if its production cost is decreased significantly. Formic acid can also be used to remove impurities on the metal surface if its price is competitive enough to replace HCl and H_2SO_4 [56]. Nonetheless, other CO_2 conversion pathways, such as syngas production, must

be utilized as well to maximize the opportunity for converting CO_2 to valuable products.

3.2.4 Renewable power generation technology options

CO_2 conversion options have considerable electricity requirement as shown in Fig. 6(a). This could make CO_2 conversion technologies infeasible to be implemented if electricity is provided from fossil fuel power plants which have significant environmental impacts. To offset the impacts of generating electricity for CO_2 conversion technologies, solar and wind power generation technology options are considered. Figure 6(b) shows the results for CO_2 conversion to formic acid with different power sources. If 1,000 t/day of CO_2 is converted to formic acid, 7.64 TJ/day of electricity is required for the conversion process. Given the barren land area in the MRW, energy potentials for solar and wind power generation in the MRW are 158 and 56 TJ/day, respectively. Therefore, there is enough land area in the MRW for solar and wind power generation for CO_2 conversion to formic acid.

If renewable power generation technology is employed for CO_2 conversion to formic acid instead of fossil fuel-based technology, the impacts from thermoelectric power generation can be avoided. Figure 6(b) exhibits the increase in V_{CO_2} and V_{H_2O} indicators by employing renewable power generation options instead of fossil power generation. Wind power option shows a higher V_{H_2O} value than the solar power option since some water resource is still required for solar power generation technology as described in Section 2.7. V_{NG^*} indicator can also be improved since renewable power generation technologies do not require the use of NG to generate electricity. The scale of those changes is very small because only a tiny portion of fossil power plants (7.64 TJ/day out of 230 TJ/day) are replaced by renewable power generation technologies for 1,000 t/day of CO_2 conversion.

For renewable power generation technologies to be economically feasible, they need to be cheaper than conventional fossil power generation. According to the U.S. EIA report, levelized costs of electricity (LCOE) for NGCC, solar (PV), and wind (onshore) power generation technologies, respectively, are estimated to be 42.8, 48.8, and 42.8 \$/kW if new generation facilities are introduced in 2023 [58]. The report also describes that the LCOE for solar and wind power generation technologies can be cheaper if federal tax credits are included for the renewable technologies: 37.6 \$/kW for solar (PV) and 36.6 \$/kW for wind (onshore). In this context, appropriate tax incentives can accelerate the use of renewable generation technologies. Economy models, such as general or partial equilibrium models, could address these tax incentives in the analysis [59].

3.3 Agroecological alternatives

Although technological alternatives can improve many sustainability indicators as described above, they only help reduce the environmental interventions from activities, which correspond to the ecosystem demands. According to the TES framework, watershed sustainability can also be enhanced by increasing the supply of ecosystem services [6]. Also, none of the technological alternatives have significant impacts on water quality indicators, such as V_{TN} and V_{TP}. As shown in Fig. 3, most water nutrient runoffs (total N and P loads) are attributed to agricultural activity. In this section, we discuss potential agroecological alternative options that include various tillage practice and available land use change options.
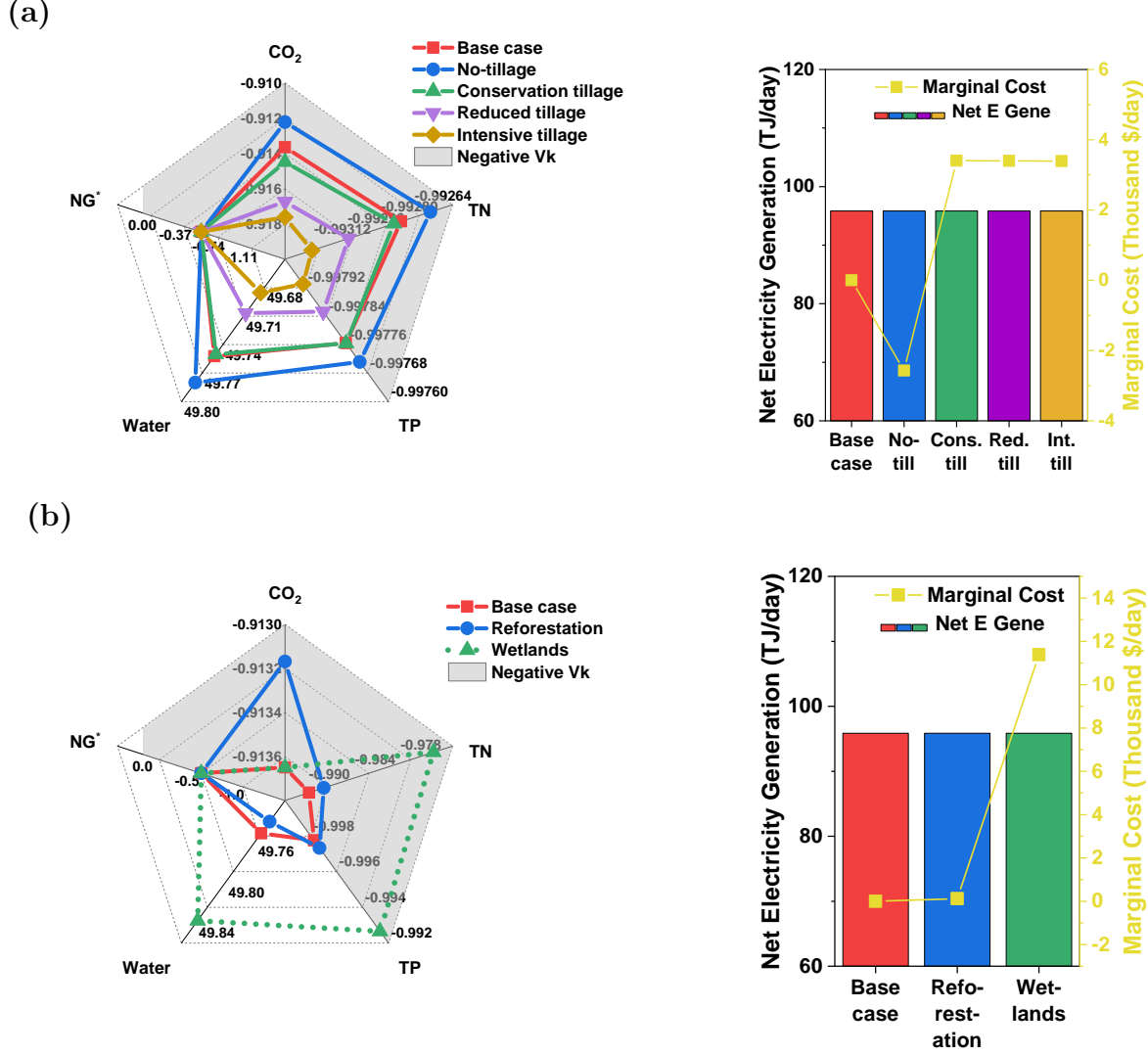
(a)

(b)

Figure 7: Sustainability indicators for agroecological alternatives. TES metrics are plotted in radar diagrams. (a) Tillage practice options. (b) Available land use change options.

3.3.1 Tillage practice options

Figure 7(a) shows the results of sustainability indicators for the base case and various tillage practice options. Unlike most technological alternatives addressed in Section 3.2, tillage practice options affect water quality-related indicators. No-till option is most sustainable with respect to V_{TN} and V_{TP} indicators. Although no-till option does help improve V_{TN} and V_{TP} indicators, changes in these indicators are insignificant. In fact, the prime mover for nutrient runoffs is precipitation rather than the implementation of certain agricultural practices. In this static analysis, however, the amount of precipitation is fixed and only the impacts of agricultural practices on nutrient runoffs are examined.

No-till farming also improves soil carbon sequestration. According to the previous study, the conversion of intensive tillage to no-till for the corn and soybean farming in Ohio can

increase carbon sequestration rate by 82.5 $gCm^{-2}y^{-1}$ [60]. If reduced tillage practice is converted to no-till, additional 69.3 $gCm^{-2}y^{-1}$ can be sequestered in soil. As a result, the increase in V_{CO_2} is obtained from the no-till option. Also, the no-till practice is cheaper than other tillage practice options. However, The no-till practice may reduce food production yield, which is not included in this analysis.

3.3.2 Available land use change options

Figure 7(b) represents the results for available land use change alternatives. If the barren land is converted to forest, V_{TN} and V_{TP} indicators are improved since tree cover helps reduce nutrient runoff through soil infiltration. The increase in V_{CO_2} from reforestation is smaller than technological alternatives although reforestation certainly increases the amount of carbon sequestration service. Since GHG emissions are much larger than the supply of carbon sequestration service, and therefore, the reforestation does not improve the TES metric for CO_2 considerably.

Constructed wetlands can be built in the available land as well. The supply of water regulation service is provided from the wetland. As shown in Fig. 7(b), the positive impacts of constructed wetland on V_{TN} and V_{TP} indicators outweigh the reforestation option. Constructed wetlands cost more than reforestation. However, this is a small cost compared to other technological alternatives.

3.4 Solutions to improve watershed sustainability

In Sections 3.2 and 3.3, various technological and agroecological alternatives are investigated to improve the overall sustainability of watershed. While technological alternatives mainly help reduce air emissions and water consumption, which correspond to the ecosystem demands, agroecological alternatives improve water quality indicators by enhancing the supply of water quality regulation service and reducing water nutrient runoffs. As best case scenarios, the following technological alternatives are selected as technological solutions: Shale NG-fired combined cycle power plants with recirculating cooling system and 1,000 t/day of CO_2 conversion to formic acid with wind power generation. Also, an agroecological solution is determined as follows: The implementation of no-till practice and the construction of wetlands on available land.

Figure 8 shows sustainability indicators for the two solutions described above. As compared to the base case results, V_{CO_2} indicator is improved for the technological solution. The reduction in V_{NG^*} indicator for the technological solution is inevitable since NG is used instead of coal for thermoelectric power generation. On the other hand, the agroecological solution enhances V_{TN} and V_{TP} indicators. Since each solution recommends alternatives to different groups of activities, both solutions can be combined to obtain synergies between the solutions. Synergistic solution includes alternatives that are selected for both technological and agroecologial solutions addressed above. As shown in Fig. 8, the synergistic solution can give a "win-win" situation between objectives.
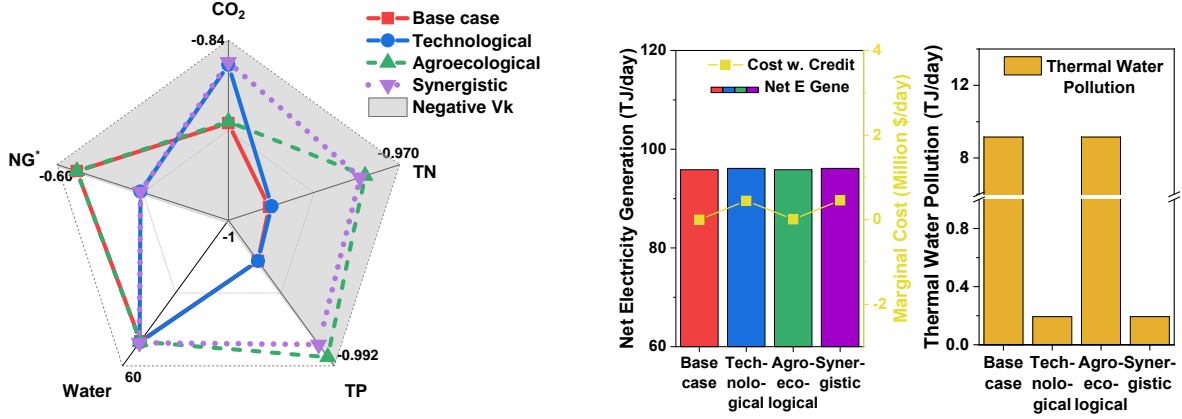
Figure 8: Sustainability indicators for best case scenarios. TES metrics are plotted in radar diagrams. Technological solutions include shale NG-fired combined cycle power plants with recirculating cooling system and 1,000 t/day of CO_2 conversion to formic acid with wind power generation. Agroecological solutions include the implementation of no-till practice and the construction of wetlands on available land. The synergistic solution combines both technological and agroecological solutions.

4   Finding Significance

In this work, various alternatives in terms of fossil power generations are investigated to identify interactions between multiple flows while addressing the energy-water-CO_2 nexus in the watershed. To examine watershed sustainability, a holistic TES assessment approach is employed since total ecosystem demands from activities in the watershed need to be compared with total ecosystem supplies in investigating if activities in the watershed are sustainable or not. From the results, it is identified that the amount of water supply in the MRW is larger than the amount of water demand for any scenarios discussed in this work. This implies that the reduction in water quantity indicator may not be a huge concern since the TES metric for water supply is still positive. However, TES metrics for other ecosystem goods and services, such as NG, CO_2, and air and water pollutants, show negative values, which indicate unsustainable conditions of activities in the MRW.

Since most of the air emissions and NG consumption are attributed to thermoelectric power generation, various technological alternatives that include different fossil fuels, cooling technologies, CO_2 conversion technologies, and renewable power generation technologies are examined. Overall, it is identified that TES sustainability metrics for carbon sequestration and air quality regulation services can be improved by employing NGCC power plants with recirculating cooling system and CO_2 conversion to formic acid that uses electricity from wind power generation. Coal option is better in terms of NG indicator, however, it has deleterious impacts on other sustainability indicators. Also, dry cooling technology has the potential to improve water quantity indicator. However, its lower generation efficiency and higher cost than wet cooling technologies may pose constraints for the implementation of technology. Moreover, improving water quantity sustainability may not be urgent for a

water-affluent region such as the MRW.

With respect to CO_2 conversion technology alternatives, stoichiometric reactions are assumed for potential CO_2 conversion technologies since data for commercialized technologies are not available at this point. It is noted that displacement credits from conventional processes also need to be considered to examine which conversion technology is better than others. It remains as future work to perform a more realistic analysis for CO_2 conversion scenarios using detailed process data and technological constraints.

Agroecological alternatives that include farming practices and land use changes are in a better position to improve water quality sustainability rather than technological alternatives since water nutrient runoffs are mainly attributed to agricultural activity. No-till farming practice and constructed wetlands on barren land in the MRW can improve TES metrics for nitrogen and phosphorus runoffs. In conclusion, watershed sustainability can be improved by considering alternatives for multiple activities. The synergistic solution that includes both technological and agroecological alternatives could produce "win-win" outcomes in terms of multiple objectives.

Some alternatives addressed in this work are superior in terms of environmental sustainability, but economically expensive. To provide more insights for the sustainable management of the watershed, the economic feasibility of alternatives needs to be investigated more thoroughly. For the robust economic analysis, the use of sophisticated economy models is required. One example is to use partial or general equilibrium models to account for market changes due to technology choices [59, 61]. Also, non-market monetary values of ecosystem goods and services need to be estimated and compared with market values of other technological and agroecological alternatives. Moreover, economic options based on nutrient trading schemes can be explored to avoid adverse impacts on water quality in the watershed since abating agricultural nutrient loadings is much cheaper than abatement at the regulated point sources [34].

The interventions from activities and the availability of ecosystem goods and services vary over space and time. Renewable energy potentials and nutrient runoffs from farming activities also vary with season. Additional energy storage systems may be needed to compensate for the intermittency of renewable energy resources. Therefore, regional and seasonal variations in those flows need to be considered. Moreover, the consequence of future climate change on watershed activities needs to be assessed to ensure watershed sustainability. Depending on future climate scenarios, water quantity indicator may not be positive anymore due to the increased risk of drought. Uncertainty analysis also needs to be performed to evaluate the robustness of results.

Considering the energy-water-CO_2 nexus in the analysis will avoid shifting of the environmental impacts across multiple flows by identifying interactions between flows. This work could be applied to any watershed to help decision-making of businesses and policymakers to improve the sustainability of watershed.

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  4. Lee, K., Khanal, S., and Bakshi, B.R. "Food-Energy-Water-CO_2 Nexus of Technological and Agroecological Alternatives for Sustainable Watershed Management." Industrial Society for Industrial Ecology (ISIE) 2019 Conference. Beijing, China.

  5. Lee, K., Khanal, S., and Bakshi, B.R. "The Energy-Water Nexus of Thermoelectric Power Generation and its Impacts in the Muskingum River Watershed in Ohio." American Institute of Chemical Engineers (AIChE) 2018 Annual Meeting. Pittsburgh, PA.

- Students Supported - Number and name of students supported by the project (MS / PhD / undergraduate / post docs) as well as their majors:

  1. Kyuha Lee (Ph.D. student in Chemical and Biomolecular Engineering)

- Profession Placement of Graduates including sector (if known and applicable) and Teaching Assistantship: None

- Awards or Achievements (patents, copyrights): None

- Any additional funding for this project:

  1. Received a support from the National Science Foundation (NSF) program on Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS) for the project titled "Dynamic regional INFEWS/T1: Impacts of deglobalization on the sustainability of regional food, energy, water systems" ($1.7 million).
  Duration: 09/2017 – 08/2020.

  2. Received a travel award from the National Science Foundation (NSF) for the Sixth Symposium on Industrial Ecology for Young Professionals (SIEYP) on July 6-7, 2019 ($1,000).