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Closing the loop: integrative systems management of waste in food, energy, and water systems

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Abstract Modern food, energy, and water (FEW) systems are the product of technologies, techniques, and policies developed to address the needs of a given sector (e.g., energy or agriculture). Wastes from each sector are typically managed separately, and the production systems underlying FEW have traditionally treated pollution and waste as externalities simply diffused into the ambient environment. Integrative management that optimizes resource use presents opportunities for improving the efficiency of FEW systems. This paper explains how FEW systems can be optimized to (1) repurpose or cycle waste products, (2) internalize traditional externalities, and (3) integrate wastes with resource inputs across systems by diverting waste by-products from one system to meet demands of another. It identifies the means for "closing the loop" in production systems. Examples include management of legacy wastes from fossil fuel industries (coal and natural gas) and integrative designs for advanced renewable systems (biogas from waste, bioenergy from CAM plants, and solar). It concludes with a discussion of how studying the governance of such systems can assist in tackling interconnected problems present in FEW systems. New governance arrangements are needed to develop solutions that can align with regulatory frameworks, economics incentive, and policies. Four aspects of governances (property rights, policy design, financing, and scale) emerge as tools to facilitate improved institutional design that stimulates integrative management, technology innovation and deployment, and community development. The conclusion offers a framework through which integrative management of FEW systems can be linked to value chains in closed-loop systems.

Keywords Closed-loop production systems · Integrated systems analysis · Bioenergy · Biogas · Hydraulic fracturing · Acid mine drainage · Irrigation · Water consumption · Public policy · Governance

Introduction

Many modern societal challenges stem from systems inefficiencies that waste resources. These inefficiencies are myriad and fundamental. Of the 103 exajoules (1 exajoule = 2.78×10^{11} kWh) of energy consumed in the USA annually, only 73 % are delivered to an end use, reflecting 27 % waste (EIA 2011). In the case of food systems, an average of 33 % of grain, vegetables, red meat, and poultry are wasted annually (Buzby et al. 2011; Giovannucci et al. 2012). Irrigation of crops that support food production consumes 135 million m^3 of water, amounting to 77 % of all water consumption in the USA, even though only 6–14 % of agriculture is irrigated in this country (USDA 2007, 2012). Improving efficiencies of the systems that supply food, energy, and water (FEW) requires major infrastructure overhaul and substantial financial investment. Near-term solutions for co-managing FEW systems more efficiently provide critical steps during a more fundamental transition to policy, economics, and infrastructure that closes the loop on waste. This article describes strategies that view wastes from FEW production as opportunities for enhancing overall efficiency if systems are managed with an integrative perspective and provides a framework for evaluating how systems might be more tightly integrated.

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Energy systems in the USA are still predominantly fueled by fossil resources, with waste products that impact air, land, and water quality. Major air pollutants from the coal industry include mercury, sulfur oxides, and nitrogen oxides, among others. Water pollutants include metals such as iron and aluminum, and sulfur that leads to acid mine drainage. Prior to the establishment of the Clean Air Act of 1970, Clean Water Act in 1972, and the Surface Mine Control and Reclamation Act of 1977, these pollutants were generally unregulated and assumed to be diluted and discarded upon discharge. Despite increased regulation and quality standards since the 1970s, the pollution from historic activity persists in the environment along with newly generated waste from modern fossil fuel extraction technologies. Horizontal drilling and hydraulic fracturing for natural gas production is a recent technological advance for the fossil fuel industry, but is the source of new methane emissions, has a high water demand, and generates a new form of waste water to be regulated.

Alternative energy systems are growing as a means to offset the impacts of fossil fuel systems. Yet systems that use renewable resources generate waste as well. The manufacturing processes associated with solar, wind, hydrogen, biomass, and hydroelectricity all consume resources and generate waste even if at a lower level than fossil fuel technologies (Pehnt 2006; Varun et al. 2009). For example, large-scale solar energy deployed in arid regions requires substantial water for cleaning to maintain efficient energy generation (Ravi et al. 2014). Some renewable energy systems, however, use waste as the feedstock for energy generation, demonstrating the potential for improving systems efficiencies by integrative management. Municipal solid waste management is an industry unto itself, but integrating energy and waste management creates opportunities for reducing life-cycle impacts of otherwise separate production processes (Cherubini et al. 2009; Münster and Lund 2009). It is estimated that animal manure alone, the largest waste resource that is uniform in format, could generate between 9 and 25 exajoule (EJ) (Hoogwijk 2003), or 7 % of global energy consumption (IEA 2013).

The US food system depends heavily on international trade despite the large agricultural land resource available domestically. Agricultural production in the USA is dominated by corn (*Zea mays*) crops, with the majority of corn grain used for livestock feed and bioethanol. There are 35 million ha (86 million acres) allocated to this one crop in the USA with only ~8 % used for human food (FAOSTAT 2015). In the USA, there has been a decline in farmland since the middle of the twentieth century as crop diversity decreased and farming in some regions was abandoned (USDA 2012). Yet, the American diet has become more diversified over the same time period through the increase of imported food commodities. With ca. 33 % of food resources wasted (Giovannucci et al. 2012), there are clear opportunities for improving the efficiency of the food economy. An alternative to reducing waste is to utilize it for other purposes. Both abandoned agricultural land and wastes can be used for bioenergy feedstocks (Campbell et al. 2013; Davis et al. 2014). Agricultural lands can also be diversified to enhance nutrition, ecosystem services, and efficiency within food supply chains (Giovannucci et al. 2012).

Food and energy systems impact water in many ways. Agriculture is the leading consumer of water. Even in the USA, where only 6 % of farmland is irrigated in an average year (USDA 2007), and 14 % in a recent drought year (USDA 2012), irrigation accounts for an average of 77 % of water consumption (Kenny et al. 2009; Scown et al. 2011). Consumption of water for irrigation is of growing concern due to risk of increased drought expected in some regions as climate change progresses, and opportunities for reducing or reusing water would greatly benefit this production system. Water resources are also affected by withdrawals that result in a change to water quality. In this case, water is not technically consumed, but is altered before being returned to the source drainage basin. Depending on the change in quality, there can be substantial chemical and biological consequences for this change. The vector of change (e.g., heat, chemical load) is a waste from the industrial system that uses withdrawn water.

The structure of economic incentives in FEW systems has led to wastes being treated as externalities. However in some cases of both current and legacy system wastes, these byproducts may offer value-added opportunities for both improving efficiency of production and reducing environmental impacts. Systems that are designed to incorporate waste back into one or more stages of production are known as “closed-loop systems.” Closed-loop systems improve the sustainability of manufacturing a product by focusing on the entire lifecycle from the extraction of raw material to disposal. It focuses on recapturing and reusing material within a process, across processes, or across different products, and the use of biodegradable/bio-compostable materials to reduce the environmental impact of production and consumption (Dekker et al. 2013; Ellen MacArthur Foundation and McKinsey & Company 2014; Winkler 2011). In the text that follows, we provide four examples of how integrated FEW systems can be designed as closed-loop production systems where waste is repurposed and utilized for multiple values along and across different production cycles. We then describe the potential for successful integrated systems management with governance that carefully addresses property right institutions, policy design, long-term financing, and scaling issues.

Example 1: coal mining waste repurposed as useful chemicals

Coal mining creates a large waste stream including tailings and, in some cases, acid mine drainage (AMD). AMD is formed through oxidative weathering of sulfide minerals exposed during the mining process and is a metalliferous, acidic waste stream. Once exposed, many underground mines continue to discharge decades after mining ceased. Reclamation efforts can treat AMD, but do not eliminate it, and create large public costs expended toward maintaining water quality. There is potential for material reuse and resource recovery to reduce the ongoing waste stream created by mining.

Reuse or processing of AMD has been investigated for three key uses: metal recovery, phosphorous removal from municipal wastewater, and hydraulic fracturing source water (Fig. 1). Each has the potential to increase the sustainability of mining and reduce the impact of AMD if the processes are made more efficient. Hedin (2006) showed that a saleable product can be extracted from AMD; the author extracts iron oxy-hydroxide sediments from treatment systems for abandoned coal mines to sell as pigment for paints and even crayons (Hedin 2006). Various extraction methods have been suggested including biochemical methods (Sahinkaya et al 2009), sequential precipitation (Matlock et al 2002; Wei et al 2005), and titration (Jenke and Diebold 1983), although few of these processes have been widely adopted. AMD is a diffuse pollutant, so a decentralized, low cost, potentially portable approach could lead to increased revenue potential and increased adoption by the industry.

The iron compounds present in AMD are known to be effective sorbents for phosphate (e.g., Dobbie et al. 2009), so much so that phosphorous availability has been identified as a potential limitation to recovery of AMD impacted waterways (e.g., DeNicola and Lellock 2015). Wei et al. (2008) and Dobbie et al. (2009) show effective phosphorous removal using iron precipitates from AMD when applied as tertiary treatment of municipal wastewater, and these results are consistent with studies describing co-treatment of AMD and municipal wastewater (e.g., Strosnider and Nairn 2010). While there is widespread potential application for phosphorous control using AMD, the proximity of either major agricultural pollution or municipal wastewater to iron-rich AMD limits widespread application of the technology.

AMD has also been explored as source water for hydraulic fracturing (Macy et al. 2015). Since hydraulic fracturing requires a large amount of water, the Pennsylvania Department of Environmental Protection has suggested use of AMD rather than freshwater as source water (PDEP 2013), and other states are following this example. Drawbacks such as trucking distances, potential for well bore scaling due to high iron concentrations, and reactions with sulfate in the AMD to form insoluble barite or toxic hydrogen sulfide gas could limit reuse of AMD for hydraulic fracturing. Efficient, low cost treatment to remove key constituents and effective planning to reduce trucking distance could allow for this reduction in waste. Integrative management of AMD and source water for hydraulic fracturing has the potential to reduce both water withdrawals and new waste in regions that still struggle to contain legacy waste from mining.

Other pathways for reusing AMD are reviewed by Kruse and Strosnider (2015), and include iron seeding in the ocean (Hedin and Hedin 2015) and sequential flooding of mine pits to maximize CO_2 sequestration (Younger and Mayes 2015). Each of these pathways is associated with other consequences that are controversial and would need to be weighed carefully against the benefits for waste remediation.

Fig. 1 Conceptual diagram of waste from coal mining (acid mine drainage) repurposed to meet resource demands within the energy industry (injection water for hydraulic fracturing) and resource demands for other markets (pigment and phosphorous remediation). Image for phosphorus remediation used with permission from Kate Heal, University of Edinburgh (www.geos.ed.ac.uk/research/cecs/water.html)

Example 2: hydraulic fracturing flowback and produced water reuse and treatment

Horizontal drilling and hydraulic fracturing are used together to extract gas, gas condensates, and oil from hydrocarbon-rich shale formations deep underground. The process requires a large volume of water (about 5 million gallons per well) that is mixed with various chemicals and produces significant quantities of wastewater (25–50 % of the injected fluid). The fluid that is injected is a mixture of water (~85 %), crystalline silica used as a proppant (~14.5 %), and chemicals (~0.5 %) including hydrochloric acid, glycols, methanol, ammonium chloride, petroleum distillates, and a number of organic chemicals that act as inhibitors and bactericides (e.g., fracfocusdata.org). The initial composition varies by producer; some states require disclosure of the fluid chemistry on the web repository, fracfocus.org, although details about some constituents are withheld due to their proprietary nature. The water that returns to the surface is termed produced water; it is "produced" when the pressure is released from the well bore, allowing the fluid to return to the surface. Management solutions for this wastewater are still needed.

The wastewater that returns within the first 10 days is called "flowback" water. The flowback portion of the produced water tends to have a composition more similar to the injected fluid than the later produced water, and makes up approximately 15 % of the produced water (Mantell 2011), depending on the shale play geology. The remaining produced water returns to the surface throughout the life of the well. Barbot et al. (2013) analyzed several hundred produced water samples; they found that "Flowback water is dominated by Cl-Na-Ca with elevated bromide, magnesium, barium, and strontium content," while over time, the produced water will be more representative of the shale formation brine, potentially including elevated chloride, bromide, sodium, calcium, barium, strontium, and radium. This large waste stream, comprised of flowback and produced water, must be managed and is typically treated for reuse through filtration and minimal removal of dissolved salts, treated for discharge using industrial wastewater treatment methods that ought to remove contaminants to meet discharge permit requirements, or disposed of in a Class II Injection Well.

Class II Injection Wells are wells used for injection of liquid waste from oil and gas operations as defined in the Safe Drinking Water Act. In the Marcellus and Utica Shale region of PA, WV, and OH, the Injection Well infrastructure is available mostly in Ohio, so produced water is trucked long distances for disposal (Mantell 2011; Lutz et al 2013; Rodriguez and Soeder 2015). Injection wells have potential problems including induced earthquakes and wastewater migration following the path of undocumented abandoned wells (Justinic et al 2013; Keranen et al 2013; Kim 2013; Rodriguez and Soeder 2015). An alternative pathway for the chemicals in produced water is needed to reduce cost and environmental impacts of hydraulic fracturing.

The clearest application of produced water reuse is for source water for further hydraulic fracturing. This is often the fate of the "flowback" portion of produced water. There are several chemical limitations to this, but Mantell (2011) reports high potential for produced water reuse. High total dissolved solids will dictate the mixing ratios between freshwater and wastewater, while high total suspended solids must be filtered out in order to reduce friction. Sulfate can drive precipitation of barite, scaling a future well, or be metabolized by sulfate-reducing bacteria to create toxic hydrogen sulfide gas (e.g., Mantell 2011; Murali Mohan 2013; Macy et al 2015). Trucking and storage are other limitations that companies must overcome for direct reuse of produced water for hydraulic fracturing.

Beyond direct reuse, there have been failed attempts at land application of produced water that led to soil degradation and vegetation damage including a test application to 0.2 hectares of Fernow Experimental Forest in West Virginia in 2008 (Adams 2011). Land application in Fernow Experimental Forest led to death of over half of the trees in the test plot within 2 years, soil had elevated sodium and chloride concentrations that decreased over time and the author suggests that the application may have impacted organic matter cycling (Adams 2011). Some jurisdictions, including parts of Ohio, Pennsylvania, and New York, also allow use of oil and gas brine for road deicing, although this practice varies widely from place to place (e.g., Schlanger 2015). Typically, no pretreatment is required; however, regulations require a certain distance between an application site and waterways in recognition of the potential for migration of contaminants into water bodies through runoff (Schlanger 2015).

Treatment of produced water is a challenging field due to the high concentrations of total dissolved solids and the complex chemistry of the fluid; fluid composition varies spatially (Barbot et al 2013) due both to the initial composition of the hydraulic fracturing fluid and local geologic conditions. Desalination (Shaffer et al 2013), membrane technologies, and thermal technologies (Rodriguez and Soeder 2015) are all suggested treatment methods for produced water. Unpublished research conducted at Ohio University aims to sequentially treat produced water to extract saleable products from the waste stream (personal communication, Dr. Jason Trembly). This is a new and growing area of research to find reliable, low cost treatment technologies that are competitive with the cost of underground injection. Integrative management of hydraulic fracturing waste with water management and other system resource demands could be a step towards more environmentally sustainable energy.

Example 3: anaerobic digestion as an opportunity for integrating waste management across food, energy, and agricultural systems

Energy generation from diversified waste streams has many benefits relative to corn, the primary biofuel in the USA today. If bioenergy feedstock were instead sourced from wastes, there would be (1) savings in both land and energy requirements (for manufacturing fertilizer, cultivation, and harvesting), (2) reduced greenhouse gas emissions from soil disturbance, and (3) reduced costs of waste disposal. It is estimated that 254 million tons of municipal solid waste are generated in the USA annually, with only 34 % recycled into other products (EPA 2015). The cost of disposal is $50 per ton, amounting to a national cost of 8.4 billion dollars spent annually on disposal of 168 million tons of food, agricultural, and landscaping wastes (EPA 2015). These wastes could instead serve as feedstocks for anaerobic digestion (AD) to generate methane fuel (gas or liquid) identical to the natural gas that is extracted from underground deposits and consumed at a rate of 29 terajoules annually in the USA (EIA 2015).

The production of methane biogas using AD is not new technology, but has only recently been developed commercially in the USA following successful examples that have emerged throughout the world in the last few decades (Aslanzadeh et al. 2014; Mata-Alvarez et al. 2000). Traditional AD efforts are focused on processing human and animal biosolids and municipal wastewaters, but there is a growing body of literature on AD of food and plant-based waste products (Kiran et al. 2014; Mata-Alvarez et al. 2011; Zhang et al. 2007; Zhang et al. 2014). The establishment of dry AD as an alternative to slurry-based wet AD has also helped advance the potential of food and other solid waste materials as desirable substrates for biogas generation (Brown and Li 2013; Michele et al. 2015).

Codigestion, AD with mixed materials instead one uniform feedstock, is also gaining increased scientific attention because sorting and processing of raw waste materials is a major limitation for system sustainability and there is mounting evidence for increased biomethane potential during codigestion (Mata-Alvarez et al. 2011; Siddiqui et al. 2014). Optimizing complex codigestion remains a challenge because the highly variable feedstock encountered in practice at the commercial scale forgoes the possibility of using one set of precise conditions. Nevertheless, there are examples of commercial AD that use multiple waste streams simultaneously. With continued research in this area, there is tremendous potential for energy generation from waste.

By-products of AD can be used for fertilizer. Unlike other pathways for converting waste to fertilizer, like livestock waste (manure) applied to crops as organic fertilizer or composted food wastes used as soil amendments, the AD system produces energy as primary product. Another example of wastes from a bioenergy production system that is used for fertilizer is the nutrient-rich by-products of fermentation in sugarcane biorefineries that are recycled backed to fields where the crops are grown. Similarly to this example, effluent from AD is used to fertilize plants cultivated as feedstocks or for other purposes. The effluent can also be applied to field crops to replace the need for conventional fertilizers that are manufactured at a high energy cost.

Prototype systems are being tested for the efficacy of managing anaerobic digestion and hydroponic vegetable production in the same greenhouse, for example at Ohio University (Fig. 2). This system is developed as an off-grid greenhouse that is passively heated by solar energy and the heat from the digester. Rainwater collected on the roof of the greenhouse is used in the hydroponic system and to make the slurry in the anaerobic digestion system. Effluent from the digester is diluted and then added to the hydroponic solution as a fertilizer. This is perhaps the best example reviewed here of a closed-loop system that includes food, energy, and water: Energy in the form of biogas and heat is produced from waste, the by-product of this energy production is used as fertilizer to grow food, the structure that houses the energy and food production collects water that cycles through both the energy and food production systems, and the waste from the food production can be returned to the digester as a feedstock. The project at Ohio University aims to determine the scale that would be required for these systems to be completed closed-loop.

Developing the infrastructure for AD systems requires investment, but when considered in the context of savings that can be made in other sectors (agricultural and waste management), this investment can be offset by both environmental and economic returns. Management that considers waste,

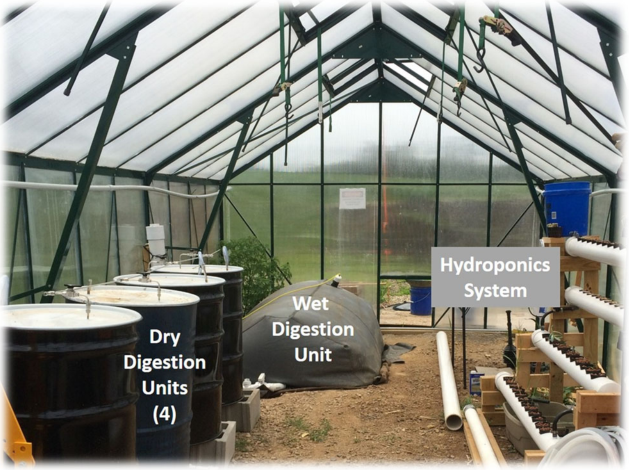

Fig. 2 Inside view of pilot-scale AD research at Ohio University where digestion units and a hydroponics system are managed together in a glasshouse enclosure to purposefully capture the wastes from one system to be used for the other. Water for both systems is obtained through a rainwater collection system (not pictured) installed on the glasshouse

energy, and agriculture under one umbrella can improve efficiency and increase environmental benefits, moving systems that are currently costly and wasteful to a more closed-loop condition.

Example 4: reduced water consumption through integrated management of renewable energy in arid regions

The focus of advanced bioenergy development goals has moved away from lands that are used for food crops or native ecosystems, and more toward degraded, abandoned, and marginal lands (e.g., Somerville et al. 2010; Campbell et al. 2013). In these conditions, that are usually less ideal for agriculture, greater inputs are required unless crop species with traits specifically suited to the environment can be identified. In arid conditions, plants that use crassulacean acid metabolism (CAM) are adapted to thrive with very low water inputs. In the USA, where 77 % of water consumption is used to irrigate 6–14 % of cropland, mostly in drier climates, there are substantial benefits to exploiting CAM species in agricultural production instead of conventional crop species (Borland et al. 2009; Davis et al. 2011, 2014, 2015; Cushman et al. 2015).

Plants with CAM photosynthesis are increasingly recognized as potential crop species that can thrive in abandoned dry land agriculture because they take up carbon dioxide through stomata at night instead of during the day (e.g., Davis et al. 2014). The cooler nighttime temperatures allow reduced water loss from the plants relative to the water lost through evapotranspiration if stomata opened during the day, as most crop species do because of their reliance on C_3 or C_4 photosynthetic pathways. Reduced water loss leads to a lower water demand. With small amounts of irrigation, CAM species like those in the *Agave* genus can yield as much as other commercial crops that receive anywhere from two to ten times the water inputs (Davis et al. 2014, 2016). Given the amount of water used in agriculture in the arid USA, and the clear difference between common commodity crops and potential CAM crops, irrigation is wasting water that might otherwise be used for other purposes.

Arid regions are often also targeted for solar development because the low level of cloud cover maximizes the radiation available for conversion to electrochemical or heat energy, either through photovoltaics or thermal solar power plants. While these systems are efficient renewable energy generators with much lower greenhouse gas emissions than fossil fuel energy systems, there is substantial water required to clean dust from the solar panels and maintain optimum power production (Ravi et al. 2014). It has recently been calculated however that the co-management of solar panels and CAM crops for bioenergy could improve the efficiency of energy generated (Ravi et al. 2014). By using the waste water from washing the solar panels to irrigate (in small quantities) CAM plants grown side-by-side with the panels, both solar energy and biomass energy production are optimized (Ravi et al. 2014; Cushman et al. 2015).

Advanced bioenergy systems require careful consideration of land resources, competing land uses, ecological suitability, and crop tolerance to climate change. The need for renewable energy sources that reduce greenhouse gas must be weighed against the resource demands required for renewable energy production. An integrative management perspective would allow resources wasted by one system to be used to meet the demands of another, in effect closing the loop on waste. Resource inputs for agricultural systems that support bioenergy vary depending on the crop species and location where the crop is grown. The example of integrative management reviewed here works in arid ecosystems, but there are parallel opportunities for integrative management of agriculture and energy in any region.

Governance of integrated FEW systems: challenges and opportunities

The diverse examples provided above demonstrate how pollution and waste can be reduced by treating them as productive inputs, and eliminating needless inefficiencies with more inclusive technical and integrated approaches. The ability to realize these gains will however challenge current governance arrangements for FEW systems to achieve tighter feedback between waste and inputs, even though significant opportunities exist for improved system design. A recent study by the MacArthur Foundation and McKinsey (2014) suggests there is an estimated $4.5 trillion to gain in economic growth from altering the current structure where by-products are treated as waste to a closed-loop system in which materials are reincorporated into production processes. Understanding how current FEW systems have evolved to miss these opportunities and how redesign can close waste systems will require examining the governance arrangements which have incentivized current production, distribution, and waste management systems.

Governance as a field of study looks at how the institutional structures of public and private economies influence outcomes. It includes a broad array of social and natural sciences that examine how social coordination is achieved to produce and implement collectively binding rules and provide public goods (Risse 2011). Governance systems are composed of institutions, defined as the collection of both formal and informal rules used for determining inclusion in decision making, what actions can be taken, the consequences of these actions, and how individual actions are aggregated into collective decisions (Kiser and Ostrom 1982; Ostrom 1990). Institutions are what structure incentives and risk, the distribution of the benefits and costs of actions, and largely influence the sustainability of natural resource systems (Hanna et al. 1996; Ostrom 2008).[1] We highlight four critical aspects of the governance arrangements around FEW systems that are challenges to integration: property right institutions, policy design, long-term financing, and scale.

1. Property right institutions and resources

Central to any resource allocation system are property right institutions (Bromley 1991). Property rights determine the flow of both rights and benefits, as well as responsibilities and costs from the use of a resource. They are particularly important in the study of integrated FEW systems as they govern what is considered an economically useful component of a resource and what is considered waste. For example, property rights to mineral resources are associated with land rights which historically have led to the benefits from mineral extraction out-valuing the damage to land and water resources. Regulatory policies have now placed an additional cost and responsibility on mineral extraction in an attempt to internalize the costs of associated environmental damages; however, these regulatory costs occurred too late to deal with historic impacts, and while the rights to the economic benefits went to private owners, the responsibilities for the negative impacts were allocated to the public in terms of environmental clean-up.

Creating systems that better align rights with responsibilities and create incentives to recycle and reuse waste streams will require new property rights structures. Emerging initiatives toward closed-loop systems such as cradle-to-cradle production have created value in the waste stream as manufacturers (1) design materials that can be reused as raw material and (2) purchase end-of-life products from consumers via up-front contracts and rebate programs (Braungart and McDonough 2002; McDonough and Braungart 2013). Contractual arrangements with consumers for material that will be incorporated back into production has effectively allocated a new property right to the waste stream as raw material, and incentivized the allocation of material for reuse and recycling directly to the manufacturer through rebate agreements.

2. Policy design for closed-loop systems

Designing effective policy instruments to incentivize and facilitate closed-loop FEW systems will entail subtle changes to property rights and the associated responsibilities. Traditionally, the policy instrument used for internalizing externalities into production decisions has been regulations, which allocate a responsibility to minimize or prevent negative externalities in using natural resources by imposing a cost (Bromley and Paavola 2002). However, these first generation policy instruments have been critiqued as not providing a reason to go beyond mere compliance, not providing significant flexibility toward improved economic efficiency, and not generating incentive to develop new technologies, or in terms related to this discussion, create new integrative closed-loop production systems (Susskind et al. 2001; Kraft and Vig 2006). Research suggests that flexibility of market-based policy instruments are favorable over that of regulatory policies for (1) stimulating the innovation of new technologies, (2) incentivizing environmental behavior beyond mere compliance, and (3) reducing the economic inefficiencies associated with regulations (Gunningham et al. 1998; Stavins 2003).

If closed-loop production is to be successful, the next generation of environmental policy instruments will need to be designed to not only mimic markets as do cap-and-trade policies, but rather to directly stimulate new resource allocation systems that create value in what are today regarded as wastes. Policy design will need to generate new systems for reducing environmental and economic inefficiencies in production systems and reframe waste as a valued resource rather than a cost in production. An example of such a program is the recent "feebate" program introduced in California in 2008 where high emissions vehicles are charged an additional fee that is used as a direct rebate for purchases of low emissions vehicles (Bunch et al. 2011). The emission waste is utilized as a disincentive for the purchase of high emissions vehicles and simultaneously provides a subsidy for the purchase of low/zero emissions vehicles. Similar programs have been proposed for landfill and waste management (Puig-Ventosa 2004).

3. Financing long-term investments

Many of the policy interventions needed to produce more efficient and effective closed-loop waste systems and tightly integrated FEW management will have to be directed at better aligning private and public interests in capital markets. Financial instruments are needed to invest and redesign infrastructure that allows integration across systems. The haphazard development of water, waste management, food system, energy production, and distribution infrastructures, including associated infrastructure for transportation and utilities, has not taken into consideration potential complementarity. Whereas waste disposal has traditionally been designed to move waste out of urban areas, integration into food and energy production will require new infrastructure investment options. For example, biogas production facilities that can utilize waste require site integration into regional plans, connection to energy supply grids, and locations on transportation

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[1] Alternative approaches within the broad field of governance studies do exist, across the theoretical spectrum. This paper uses that within the positivist political economy tradition in order to focus on incentives that structure the reduction of negative economic externalities.

networks that can allow access to waste products (e.g., sewage facilities, food water, agricultural and landscape waste) rather than being isolated from the locations where wastes are produced and situated far from energy production and demand.

Existing capital markets are poorly suited for funding infrastructure and projects that can improve long-term resource efficiencies but that cannot be translated into short-term economic efficiency, increased revenue, or reduced risk (Labatt and White 2003). For example, bonds are associated with the jurisdictional entities that offer the backing to secure investment risk (municipalities, states, nations) and provide a poor fit to resource systems that cross jurisdictional divisions at a regional and even international level. The Water Infrastructure Finance and Innovation Act (WIFIA), a major source of funding for water infrastructure in the USA, has heavy federal oversight and is considered too inflexible for meeting the needs of green infrastructure and closed-loop financing. Green bonds, a relatively new financial tool, have been critiqued as being poorly linked to environmental outcomes and more about branding than actual impact (The Economist 2014). A new generation of financial instruments will be needed to improve infrastructure and promote projects that gain value from integration, instead of funding separate independent initiatives.

The risk burden for investments in FEW has a number of characteristics particular to the integrative nature of the desired systems. Financial instruments and incentives will need to take into account (1) how risk is managed by agricultural producers, (2) investors in the infrastructures needed to process and move waste materials, and (3) the incentives facing investors in both small-scale projects and large regional infrastructure. The importance of understanding risk is ubiquitous. For example, corn has emerged as the dominant biofuel crop due to the existence of multiple markets for the product and the ability of a farmer to use this as a hedge against risk in commodity price changes for any single market. Depending on demand, it can be sold for animal feed or as biofuel feedstock, as well as qualifying for federal farm subsidy programs (Demirbas 2008; Hochman et al. 2008).

Similarly, many production activities occur within a larger supply chain of multiple producers and suppliers interacting to manufacture a final product. Innovation is curtailed by limits on how an individual action will interact with other components of the system. For example, the ability of a producer to switch to alternative crops for biofuels will require more than a single buyer in the marketplace, otherwise producers subject themselves to the prices the buyer is willing to offer in a non-competitive market, as well as price volatility from the supply chain of the buyer in using the stock for a biofuel, which may be subject to political uncertainty due to government subsidies and competing biofuel sources. In order to create incentives to cultivate alternative crops for a new market, the relative risk from entering these new markets will need to be offset. Private/public partnerships and policies that can explicitly support new technologies and bear the risk of innovation are beginning to enter policy discussions (see Leyden and Link 2015; Mazzucato 2013).

4. Scaling interventions

The level of risk associated with innovations in integrating waste in FEW systems will change with the scale of development. Trade-offs exist in the scale of the interventions intended to foster greater integration and feedback across the FEW sectors (Hill and Engle 2013). FEW systems exist at multiple spatial scales, from community and local government to state, regional, national, and international. What determines the appropriate scale of any policy intervention will depend on the size of three existing systems: natural (watershed, river basin, land), social (markets, communities, regional economies), and built systems (water infrastructure, energy grids, transportation network) relevant to the specific policy challenge (Wilson et al. 1999; Ostrom 2012).

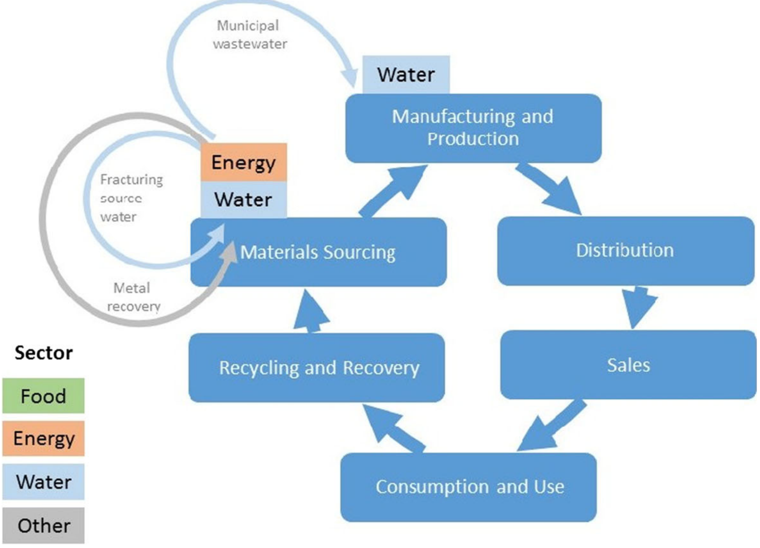
Smaller scale interventions will tend to better fit local conditions while larger scaled innovations have the potential to achieve economies of scale and scope (Oates and Portney 2003; Kauneckis and Andersson 2009). In terms of environmental benefits, the regional scale (defined by climate and land use parameters) may grant the greatest overall gains due to regional differences in energy systems and hydrological regimes and food production; however, small scale (community level) systems allow for greater experimentation. Some combination of nested governance systems that recognizes the importance of local heterogeneity in natural systems, built infrastructure, and local preferences within large-scale systems of regulatory policy and national markets will certainly be necessary (Ferraro 2003; Adger et al. 2005).

One explicit trade-off in scaling systems is how to control “leakage,” the phenomenon of forcing environmental externalities outside the system of study. Local systems that close the loop on waste may simply lead to larger waste streams outside the system. A second major challenge with utilizing current research on scaling policy interventions is how to incorporate the networked nature of modern economies and global supply chains.

Closing the loop on waste in value chains at the FEW nexus

Closed loop systems provide an opportunity to decrease the environmental impact of waste by-products while improving efficiencies in the production cycle. Figure 3 represents the four examples (described above) of potential waste streams being incorporated as inputs back into energy, food, and water systems. Each figure uses a modified version of a closed-loop

A Acid mine drainage waste extracted



B Potential uses for hydraulic flowback water to be developed

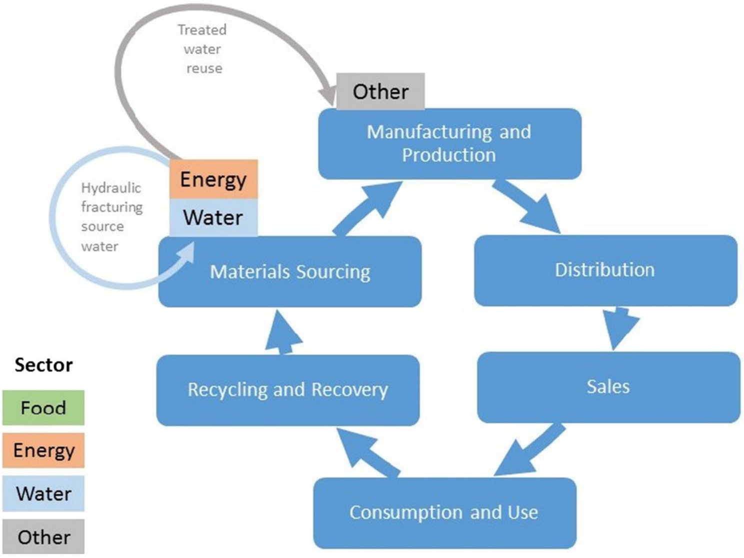


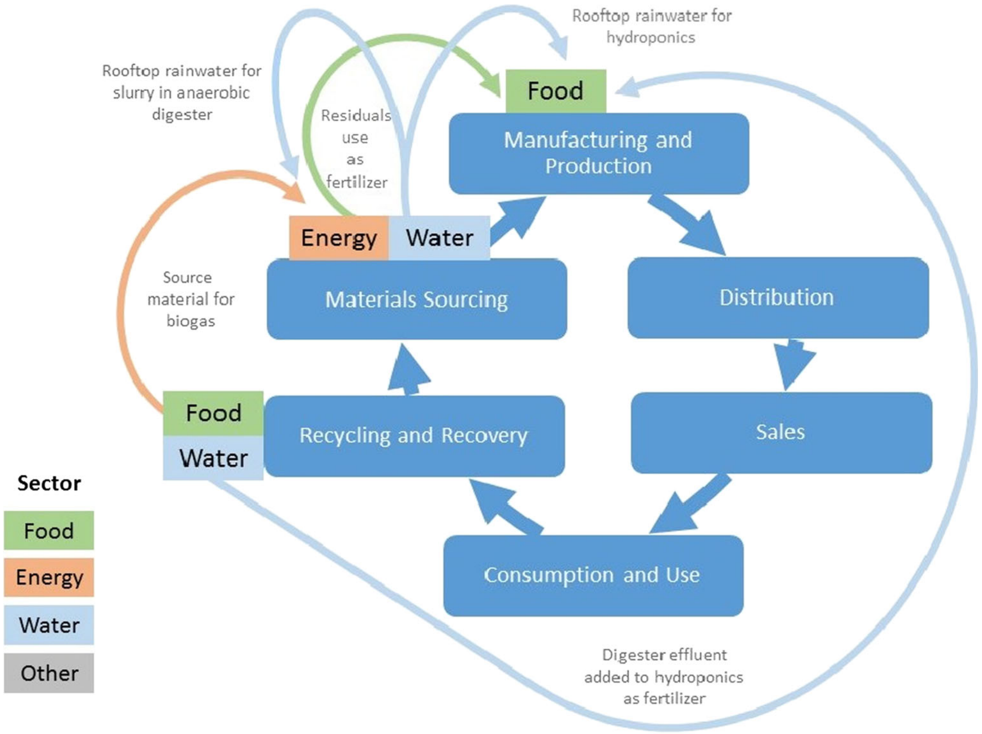
Fig. 3 Schematic of closed loop value chain for acid mine drainage (AMD) wastes (**a**), hydraulic fracturing flowback (**b**), anaerobic digestion (**c**), and crassulacean acid metabolism (CAM) plants for bioenergy on arid lands (**d**); each depicted in a life-cycle framework for closed-loop systems

value chain originally presented by the World Economic Forum (2009). There are six stages of the life cycle of a product: materials sourcing, manufacturing and production, distribution, sales, consumption and use, and recycling and recovery. While the examples discussed here primarily improve the material extraction and recycling/recovery stages, other waste products could be looped in to different stages of the life cycle. In order to illustrate interactions across FEW sectors, the sector in which the waste is produced is color coded and labeled in each figure, and the sector into which the waste product is being looped is color coded as food, energy, water, or other.

Figure 3a illustrates the potential loops of acid mine drainage wastes. The waste occurs at the nexus of energy and water in the materials sourcing phase of energy production from coal. The waste of AMD offers three potential loops back into production activities. These include the use of AMD in treating municipal wastewater, which uses a waste product from the energy sector directly as an input into the water sector. AMD is actively being explored for use in hydraulic fracturing as a water source. Finally, metal recovery from AMD has been used as a pigmentation material from a production cycle other than FEW.

Figure 3b represents the potential uses for waste water from hydraulic fracturing, both as re-usable source water for hydraulic fracturing activities and as treated water for reuse in other sectors. Both of which have significant technical

C Anaerobic digestion for food and agricultural waste



D Renewable energy from CAM plants and solar energy on arid lands

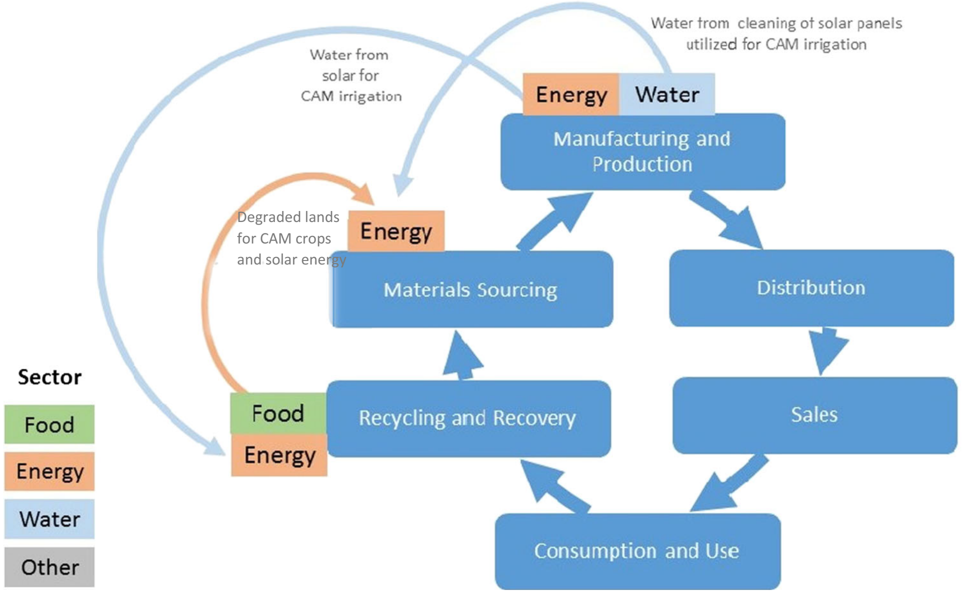


Fig. 3 (continued)

challenges in restoring water quality for either use. Solutions for waste reduction in this example have been the least developed. To contrast, anaerobic digestion systems by definition consume waste. Figure 3c shows how anaerobic digestion for the production of biogas links the food and energy sectors and reduces water consumption. Recycled food waste becomes source material for biogas production, and residuals from biogas can then be returned to the food system (or other agricultural production systems) as fertilizer. With integrative management of food and energy production in a greenhouse-like infrastructure (as depicting in Fig. 2), it is also possible to internalize water management and cycle water through both production systems (Fig. 3c).

Figure 3d includes the waste loops that can be accomplished through integrated renewable energy systems for arid regions. Degraded agricultural lands can be used for the growth of CAM crops that are then used for bioenergy production. This agricultural activity has the potential to replace agricultural systems with greater water input demands, reducing water consumption. Solar energy systems can be co-located CAM crops so that the water used in the maintenance of solar panels can provide the minimal irrigation needed for the crop. Additional value chains (not depicted) could be created through waste system loops in other phases of the life cycle.

Analyzing opportunities for closed-loop systems through a governance framework

Analyzing FEW systems through a governance framework is critical for understanding the potential of implementing emerging technologies and techniques. Challenges and opportunities for incorporating waste streams into and across FEW systems are globally common if locally specific, making this research widely applicable across a variety of scales and locations. Opportunities for integrated systems are often context-specific and depend on local conditions. The examples of AMD, biogas production, and the production of renewable energy on arid lands all involved local governance challenges.

When reviewing the example of AMD in light of the governance framework outlined here, a specific challenge for governance that would not necessarily apply in other examples emerges: how to assign responsibility for a legacy waste. AMD, a continuously generated waste that could have other uses, e.g., for pigment, phosphorus remediation, or fracturing water (Fig. 1), is the product of mining that occurred historically and the entities responsible are no longer liable in many cases. Neither is there any expectation of being able to end this waste stream. Coal mines are so extensive and continuous underground in the Appalachian Region for example that the source of the waste cannot be contained. Iron extracted from this waste may be a resource produced into the foreseeable future, but property right institutions and policy design will both require greater direct governmental and citizen involvement than cases where a manufacturer of waste can be directly involved. Long-term financing is essential and might be incentivized through economic stimulation associated with products. The scale of the resource in this case might be assumed as fixed if the current mining practices immediately remediate effects of new AMD under modern law.

In the case of biogas production that makes use of wastes from food systems and agriculture while yielding energy and fertilizer, governance issues are very different. The challenge for this system lies with unifying producers from economic sectors that have traditionally been isolated from one another. Contractually obligated property rights would incentivize the use of waste for value-added products. The “feebate” approach would allow partnering manufacturers to save costs for waste disposal by offsetting the cost with a subsidy directly linked to the usage of waste. The scale of development in this case should be expected to change because biogas production is not yet widely practiced in the USA.

Renewable energy production on arid lands might face fewer challenges for governance due to public perception of problems related to drought in this region. In the western United States at least, there are already practical incentives for reducing water consumption. Water resources are expensive, creating clear opportunity for technologies with lower production costs. Here, awareness of the best alternatives and most beneficial partnerships would require policy design that promotes research.

Vision for integrated systems that close the loop on waste in FEW requires a governance framework that encourages dialogue among traditionally independent sectors of the economy. Creative solutions for converting waste to resources in a closed-loop infrastructure demand institutional frameworks that reward internalized waste management and partnering of manufacturers. Figure 3 summarizes how integrated systems can be used to minimize externalities and promote waste as a resource. Every opportunity for integrative management would benefit from research that targets optimized solutions for closed-loop infrastructure because solutions, and partners capable of achieving them, have not yet been clearly identified in many cases (e.g., hydraulic fracturing). Research can benefit from the interdisciplinary perspective offered here that links technological innovation to a governance framework that encourages progress toward harmonized environmental and economic sustainability.

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