Supporting Information
Coordinated Markets for Scalable Management of Organic Waste and Derived Products

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1 Perspective on Organic Waste Management

Urban, agricultural, and food sectors produce significant amounts of organic waste (mostly in the form of livestock waste, food waste, and biosolids from wastewater processing). To give some perspective, the dairy sector in the U.S. State of Wisconsin is a 43 billion USD enterprise that manages 1,270,000 dairy cows [1, 2] and provides 29 billion gallons of milk and 2.8 billion pounds of cheese annually. A single dairy cow produces approximately 6,800 gallons of manure per year and the entire sector generates 8.7 billion gallons of manure per year [3, 4]. Moreover, it is estimated that 30% of all dairy food products supplied by the sector are wasted [5]. Waste management operations (collection, processing, and disposal) are becoming increasingly troublesome and costly due to ever increasing volumes of waste streams, their highly distributed nature, and their complex bio-physico-chemical composition. When left untreated, organic waste releases excess nutrients, chemicals, and biological agents to the soil, surface and ground waters, and emissions to the atmosphere, ultimately disrupting natural ecosystems. Nutrients in livestock waste and biosolids such as phosphorus and nitrogen accumulate in surface water bodies (e.g. lakes, ponds) triggering algal blooms and degrading the quality of water resources [6, 7]. Decreased water quality ultimately impacts health and socio-economic activities that are fundamental for some regions (e.g., tourism, real estate, swimming, sailing, fishing). To give some perspective, in the State of Wisconsin, the estimated annual phosphorus (P) input from livestock manure application as fertilizer is 103 million pounds while the input from synthetic

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fertilizers is 96 million pounds [8]. The total estimated P removed from crop production (corn grain, silage, hay, and soybeans) is around 150 million. Consequently, the accumulation is on the order of 50 million pounds per year. From this surplus, it is estimated that nearly 3 million pounds of P are lost to water bodies through runoff. P surplus arises because manure is often over applied as a fertilizer by farmers in order to match crop nitrogen needs and/or because farmers might have insufficient land base available for manure application. Moreover, farmers usually have an incentive to overapply fertilizer in order to mitigate risk associated with weather, soil conditions, and crop yields [9]. In several areas of the state, the amount of P accumulated in the soil has reached levels that can cover crop P needs for 20 years. This accumulation of P increases nutrient loses contributing to the diverse environmental and human health impacts across the region [10]. Current management of livestock manure is not sustainable and scalable, endangering the economic prospects of the dairy industry. In addition, organic matter contained in livestock waste, food waste, and wastewater generates harmful and odorous pathogens and gases (e.g., methane and ammonia) that leak to the atmosphere. For instance, landfills were the third largest anthropogenic source of methane in the U.S. in 2016 (accounting for 14% of the total methane emissions [11].

Mismanagement of organic waste represents not only an environmental hazard but also a lost economic opportunity. In particular, at current fertilizer prices, the dairy cow population in the State of Wisconsin produces on the order of 200 million USD worth of manure fertilizer. Diverse organic waste processing technologies are also available to generate value-added products such as fertilizers, fuels, and electricity. The EPA's AgSTAR program [12] reports that about 8,000 U.S. farms could support biogas systems, providing about 1,670 MW of electricity (enough to power one million homes) and reduce methane emissions by 1.8 million metric tons of carbon dioxide equivalents (this corresponds to taking 6.5 million cars off the road). Energy generated at the 16,000 wastewater treatment plants (WWTPs) available in the U.S. could potentially meet 12% of the national electricity demand and energy generated from 50% of the total food waste could meet the demand of 2.5 million homes [13]. In the State of Wisconsin, P recovered from manure and WWTP biosolids could generate a total economic value on the order of hundreds of millions of USD [14]. In 2009, it was estimated that P available from human urine was approximately 1.68 million tonnes globally (with similar mass available from biosolids) [15]. P recovery from these waste sources could cover 22% of the total P global demand. Moreover, new technologies are currently being investigated to produce high-value specialty chemicals such as fatty acids from livestock and food waste [16, 17]. Recovery of products from organic waste can thus help create circular economies and mitigate the use of valuable and finite mining and fossil resources. Unfortunately, economic viability of waste processing routes strongly depends on economies of scale, on transportation costs, and on the composition of the waste streams (which is complex and highly variable). For instance, anaerobic digestion and nutrient recovery technologies are often only profitable at large concentrated animal feeding operations (CAFOs) and at large WWTPs. Specifically, according to the American Biogas Council, of the 16,000 WWTPs in operation in the U.S., only 10% have adopted production of biogas. Moreover, of the 8,000 animal farms that could economically support the production of biogas, only 3% have working installations [18]. An important obstacle that hinders the installation of biogas facilities in the U.S. is the fact that low electricity rates are currently being offered by local utilities for purchasing electricity produced from biogas [19]. Another key obstacle associated with waste processing is the lack of cost-effective alternatives to collect and transport large amounts of organic waste over long distances. In particular, transporting livestock waste via hauling trucks only makes economic sense for distances under 5 miles and collecting food waste in urban areas is logistically challenging and resource-intensive [20, 21]. These technical challenges ultimately hinder investment and distort the perceived value of waste resources. For instance, economic studies have shown that the perceived value of livestock manure by CAFOs can range from positive to negative, depending on the size of the operation [22]. Other key decision makers (e.g., urban populations) are often unaware of the potential uses of their waste streams (and thus of their inherent value) and are often unaware of their fate and indirect/direct impact. Misconceptions and lack of information hinder the search for more effective waste management routes.

Diverse government regulations and incentives are currently used to promote waste management and investment in processing technologies. For instance, a nutrient trading program is currently being implemented by the State of Virginia for managing nutrient (P and N) runoff to the Chesapeake Bay watershed. Under this program, WWTPs in the region can earn nutrient credits worth 4.60 USD per pound of N and 10.10 USD per pound of P removed below permitted discharge concentration values [23]. Similar incentives are currently used to accelerate the deployment of waste processing facilities to recover biogas and liquid fuels. Specifically, renewable energy credits (RECs) and renewable identification numbers (RINs) are used to incentivize the generation of renewable energy products [19]. Unfortunately, existing incentives have not been fully capable of overcoming techno-economic and logistical costs associated with waste processing. As a result, the waste management infrastructure remains limited and fragmented, presenting a significant obstacle to mitigate the deterioration of water, land, and air resources as well as to enable sustainable growth of urban, agricultural, and food sectors. For instance, while scalable transport infrastructure for wastewater in urban areas currently exist, no scalable solutions currently exist to transport livestock waste in rural areas [24]. Moreover, there are significant inefficiencies in processing and recycling wastewater and livestock waste at a large scale [25]. The lack of suitable infrastructure is tied to the current lack of mature markets that promote a more systematic valuation and exchange organic waste and derived products and that enable systematic monetization of avoided environmental damages and remediation costs. This can be enabled by using coordinated management systems that exploit interdependencies between organic waste producers and food, water, chemicals, and energy infrastructures and that can properly monetize economic and environmental impacts associated with the deployment of more effective practices and technologies.

2 Perspective on Coordinated Markets

Coordinated markets provide a systematic framework to enable exchange of products in complex decision-making environments that involve large numbers of stakeholders, that rely on shared infrastructures, and that are driven and constrained by complex spatio-temporal physical phenomena and externalities (e.g., extreme weather). Highly advanced coordinated markets are currently used throughout the world to manage and provide access to infrastructures such as electrical power and computer networks [26, 27]. Coordinated markets for the U.S. power grid, in particular, have reached a high level of maturity over the last 30 years. Our work is motivated by the observation that the evolution of power grid markets provides important lessons and significant empirical evidence that can be leveraged to justify the need and guide the design of organic waste markets and associated infrastructure. Here we motivate our work by providing a high-level perspective of coordinated electricity markets in the U.S.

Coordinated *wholesale* electricity markets are used in the U.S. to exchange electrical power across wide geographical regions. The stakeholders in the market (the market players) comprise suppliers (companies that own power generation technologies), consumers (industrial consumers or utility companies that distribute power within urban areas), and transportation providers (companies that own the transmission network infrastructure). Power transactions over the geographical region are coordinated in real-time by a non-profit organization known as an independent system operator (ISO). In the U.S., there are currently six ISOs (California, PJM, Midcontinent, ERCOT, New York, and New England). ISOs provide an open-access system and receive bids in real-time from all suppliers and consumers connected to the network. The bidding information is used to run a highly sophisticated power coordination system (also known as power scheduling, dispatch, or market clearing system) that captures physical laws and constraints that govern generation and transmission infrastructure. Specifically, generators are physically constrained in their ability to dynamically ramp up and ramp down their power output, power flows along paths of least resistance in the transmission network, and the network is limited by line capacities and by its topology (connectivity). Capturing these physical laws and constraints in transactions is a critical need and distinctive feature of power grid markets compared to other commodity markets. The existence of the power grid infrastructure and of associated markets is driven by a fundamental social service: the need to provide efficient and reliable supply of electricity to a vast population of consumers (which is essential to perform socio-economic activities). Efficiency ensures that only the most cost-efficient resources and assets are used which drives technological innovation (e.g., new generation and transportation technologies). Reliability ensures that supply can be maintained under diverse externalities that impact the power grid such as heat waves, cold fronts, storms, earthquakes, manmade attacks, and equipment degradation and failures. To give a perspective on the economic impact of reliability, ISOs currently estimate the value of lost power (also known as the value of lost load) to be up to 30,000 USD/MWh (while the average electricity price in the U.S. is 20 USD/MWh) [28]. This value is estimated based on the socio-economic impact of lost electrical supply service [29, 30]. The need to coordinate power transactions in space and time is thus essential to ensure that the infrastructure provides adequate service to society. PJM currently operates the largest market, which serves 65 million customers across 14 states and manages 1,376 generation sources, 82,000 miles of transmission lines, and 6,038 transmission substations. The PJM day-ahead market updates price signals every hour for 10,000 different locations. Achieving high reliability for systems of this magnitude (which also face constant changes in the number and locations of consumers and generation technologies) would be challenging and risky under an uncoordinated market.

The design of coordinated markets currently operated by ISOs has involved a careful consideration of economics and physics [31]. Specifically, current clearing procedures are designed to determine power allocations that are physically realizable and price signals that properly incentivize generation, transport, and consumption. Specifically, prices are generated in a way that they cover the operating costs of generators. Moreover, spatial price differences are designed to remunerate transportation providers through mechanisms such as financial transmission rights [32]. Allocations and price signals are generated by solving an optimization problem that seeks to maximize the social welfare (service value minus supply cost across the region) subject to the physical laws and constraints governing the infrastructure. Price signals encode effects of physical, temporal, and spatial constraints (which impose market friction). Specifically, shortage of power at a given point in space and time (e.g., due to transmission network congestion or lack of ramping up capacity) will manifest as a large price. On the other hand, excess of power at a given point in space and time (e.g., created by the inability to ramp down generation) will manifest as a small (or even negative) price. Price signals and allocations generated by the clearing system also have the key property that they are the outcome of a competitive market equilibrium. This is key, because it implies that the ISO does not interfere with transactions between suppliers and consumers (it only ensures that physical compatibility is achieved in the transactions).

Price signals serve as natural catalysts that drive and justify infrastructure investment and technology innovation. For instance, large spatial price differences indicate that opportunities exist to invest in new transmission lines and large temporal price differences indicate that opportunities exist to develop fast power generation and storage units [33, 34]. Electricity prices are also a key factor that influences location of industrial facilities (e.g., manufacturing and data centers) [35]. Another important benefit of coordinated markets is that they provide a systematic framework to monetize environmental impacts of power grid infrastructure and to predict the effect of government incentives and regulations. For instance, understanding impacts of water usage and emission constraints on the flexibility of power plants and on prices is essential in developing environmental regulations and policies [36, 37]. The coordination scope of power grid markets is currently being expanded to capture physical constraints of the natural gas infrastructure [38]. This is driven by the increasing dependence of power plants on natural gas and by the fact that the natural gas infrastructure exhibits drastically different spatiotemporal physical constraints (e.g., gas networks exhibit significant delays and have sparser topologies) [39]. The need to coordinate with other infrastructures and markets will likely persist, due to the increasing interdependence between the power grid with transportation, water, communication, and computing infrastructures [40, 35].

Uncoordinated and semi-coordinated organic waste markets are currently in operation across the world. The Office of Fair Trading in the United Kingdom conducted an organic waste market study in 2011 that focused on sewage sludge [41]. The study found that competition and communication in the sewage sludge market is limited and that sludge transactions between WWTPs is rare and negotiations are ad hoc. Nunan [42] documented the development of urban organic waste markets using a case study of Hubli-Dharwad, India. Before 1997, the Hubli-Dharwad Municipal Corporation sold waste to farmers by auction activities where the seller and farmer reached an agreement on the prices. After 1997, no auctions have been held, and farmers buy municipal solid waste by contacting the Hubli-Dharwad Municipal Corporation directly. The Hubli-Dharwad Municipal Corporation has also asked private sector companies to tender bids for the provision of solid waste processing. In the U.S., impacts of waste on water quality have been addressed by using carbon and nutrient credit trading initiatives guided by the U.S. Environment Protection Agency and the U.S. Department of Agriculture [43]. In the nutrient credit market, suppliers generate nutrient credits through conservation activities, and customers buy credits to meet regulatory requirements. However, in the three pilot programs in Wisconsin, the nutrient trading is not considered an active way to manage water quality [44].

Semi-coordinated markets act as brokers that connect suppliers with consumers. In Europe, for example, the European Energy Exchange (EEX) group facilitates trade of energy, environmental credits, and agricultural products [45]. Semi-coordinated markets certainly facilitate transactions but do not capture system-wide interdependencies and physical constraints associated with transportation and transformation. As demonstrated by coordinated electricity markets, capturing these system-wide effects is essential to achieve high efficiency and scalability. Recent studies have advocated for the need of coordinated organic waste markets that can enable a free movement of waste in order to facilitate processing and recycling as well as to provide incentives for waste generators (e.g., livestock producers) to manage animal waste and associated environmental impacts [46, 47, 48]. Such recommendations are also justified by research studies that develop economic models to capture system-wide geographical, physical, and logistical issues. For instance, Corrales et al. [49] developed a GIS-based watershed assessment model integrated with an economic model to compare nutrient trading scenarios in an agricultural sub-basin of the Lake Okeechobee watershed in Florida. The results show that a coordinated nutrient trading market leads to cost savings. Innes [22] developed a spatial model of regional livestock production that captures environmental impacts associated with spills from animal waste storage, nutrient runoff due to the application of manure to croplands, and direct ambient pollution. The model was used to analyze the impact from policy effects including scare regulations, fertilizer taxes, and waste handling standards affecting storage and transport. This model provides a number of intriguing and counter-intuitive insights that highlight the complex interdependencies that exist in organic waste management. For instance, it was found that fertilizer taxes in fact increase the welfare of livestock producers. Capturing interdependencies that arise from product transport, processing, and spatial layouts of sources and demands is essential to design and predict the effect of policies.

3 Significance and Uses of Coordinated Market

In electricity markets, demand bidding costs for inflexible consumers (such as urban areas) are usually set to a large value known as the "value of lost load" (VOLL), which quantifies the lost economic opportunity that arises from the power grid not being able to provide a service to society. The magnitude of VOLL is often estimated by performing detailed studies on the potential value of critical functions enabled by the provision of electricity. High VOLL values exert socio-economic pressure to markets (it activates the markets). In the absence of this external pressure, suppliers might not have a natural incentive to serve electricity demands at certain times and/or locations. In the context of organic waste markets, a similar socio-economic pressure exists but manifests as the need to process waste (as opposed to disposing it to the environment). This pressure can be captured in our framework in the form of consumers (the environment) with negative bidding costs. Analogous to the case of VOLL, negative bidding costs for the environment can represent *value of service* (VOS) and can be estimated by determining environmental remediation and human health costs associated with leaving waste untreated. The need to determine suitable magnitudes for VOS at different geographical locations will create an incentive for government agencies to properly quantify local socio-economic, health, and environmental impacts associated with waste disposal. Negative consumer bidding costs will activate the market because they force clearing prices to be negative, creating an incentive for transformation providers to purchase waste (and getting paid for it) to produce valuable products. This basic principle drives the existence of infrastructures for wastewater treatment facilities (which transform wastewater into higher quality/value water). A negative bidding cost will also create an incentive for waste disposal providers, which is the basic principle driving landfill operations. Consequently, the proposed market can help determine suitable gate/tipping fees.

Prices generated under the market framework can help justify investment in infrastructure and technology innovation. For instance, WWTPs and local governments need to justify investment in new technologies to their stakeholders (citizens served). In particular, one could use market prices for biosolids with high and low P concentrations to justify the need for investment in a P recovery technology. Developing a mature market with more predictable prices is also essential in minimizing investment risk. A coordinated market framework can also help set best practices to characterize and price complex organic waste streams and derived products and with this standardize waste exchange practices. Electricity markets, for instance, use a standardize framework to report bidding values. Moreover, competition induced by markets fosters disclosure of true values for products and technology operating costs.

Market prices obtained from the proposed framework can also help inform and foster transactions between diverse market players in urban, rural, and industrial sectors. For instance, a coordinated market can help promote food waste separation and composting practices. One can also envision deploying coordinated markets in a hierarchical manner (as is done in electricity markets). For instance, one could create a coordinate market per county and have the county markets coordinate in a regional (state) market. States market could then be coordinated in a national market. This hierarchical organization arrangement can enable management of a large number of market players and facilitate cross-regional transactions. This can be exploited, for instance, to identify nutrient-deficient regions in which excess manure fertilizer and associated nutrients can be more valuable. In other words, coordinated markets can help balance (homogenize) nutrient budgets across counties and regions more effectively as well as identify processing options needed that facilitate long-distance transportation (e.g., pelletization) [50, 51].

A market framework enables fast system-wide adaptations of allocations and prices to respond to spatiotemporal externalities. Specifically, the allocations and prices generated by the clearing procedure implicitly capture geographical priorities and transportation constraints. For instance, negative demand bidding costs with large magnitudes can be used to capture endangered areas (e.g., regions with high nutrient concentration in the soil and water bodies). This will naturally create *price re-*

gions that reflect how valuable or undesirable a particular waste stream is. Because the market will be cleared on a rolling basis (i.e., say daily), market players can adjust their bids to capture natural fluctuations of weather and other externalities. For instance, bidding costs can be adjusted during the raining season to prevent the application of manure in a certain area, which can lead to in-excess run-off, nutrient pollution, and harmful algal blooms which pose severe toxicity risk for communities, livestock, and wildlife. In this case, waste prices will implicitly capture the fact that an area will be endangered during a particular season compared to others when it is safer for manure to be applied. The market framework will thus provide a more natural (and economically) sound mechanism to prevent application of manure at certain times (as opposed to simply forbid application). A coordinated market framework also provides a systematic approach to enable concerted and effective responses to externalities that might threaten urban and rural activities (such as droughts and extreme weather events). *Resilience* provided by coordination is in fact one of the main drivers behind coordinated electricity markets. Along these lines, a coordinated waste market can help identify new pathways to produce and use electricity. As a result, coordination of waste and electricity markets can potentially achieve mutual benefits. For instance, current electricity rates provided by utility companies to biogas-based electricity producers in the US are too low to justify investment in anaerobic digestion and associated infrastructure. Coordination of electricity and waste markets can thus help provide a more systematic approach to uncover the true value of electricity generated from waste.

Prices obtained with the market framework can also help create incentives and justify the installation of livestock manure storage facilities (to prevent application at certain times). In particular, under the proposed framework, prices provide a reflection of the time value of waste and of the associated environmental damages that storage and relocation can help overcome. Currently, small dairy farms are consolidating into increasingly larger operations to exploit economies of scale and reduce production costs. Consolidation, however, has the effect of concentrating livestock waste and associated environmental impacts in smaller areas. Moreover, the human population is increasingly being concentrated in urban areas and this creates a wider separation in the food and waste supply chain. Prices obtained under the proposed framework will provide a reflection of the costs associated with consolidation that urban planners and farmers can use to identify suitable degrees of consolidation and/or to identify optimal locations for operations. A coordinated market framework can also help predict the effect of incentives such as RECs, RINs, and nutrient discharge and emission constraints on social welfare and prices. In addition, this framework can inform stakeholders to optimize the investment of funds for incentives associated with organic waste management and to minimize the impacts of regulations on the economy and business.

The market framework can be used to explore potential impacts of fundamental changes in infrastructure options to process organic waste. For instance, in Sweden, households are designed to separate urine from other biosolids, which can be processed separately to recover P [15]. Fundamental changes in infrastructure are expensive and can involve complicated debates regarding public perception on health hazards. Coordinated markets can facilitate such discussions by providing information on how infrastructure changes can impact environmental remediation and product prices and how changes can create new economic opportunities for stakeholders involved (e.g., householders and livestock producers).

4 Illustrative Case Studies

In this section, we provide simple case studies that illustrate the concepts and capabilities of the proposed market framework.

4.1 System with No Transformation

We consider a simple market setting (labeled as A) consisting of one supplier (connected to node n_1), two consumers (connected to nodes n_2 and n_3, respectively), and two transportation providers that can connect players along paths $n_1 \rightarrow n_2$ and $n_1 \rightarrow n_3$. There is no transformation of waste in this setting. The supplier offers waste with a capacity of $\bar{s}_1 = 10{,}000$ tonne and it provides a bidding cost α_1^s. The consumers offer to buy up to $\bar{d}_1 = 3{,}000$ tonne and $\bar{d}_2 = 5{,}000$ tonne, respectively, and provide bidding costs α_1^d and α_2^d. The transportation providers offer to move product along path $n_1 \rightarrow n_2$ at cost α_1^f and along path $n_1 \rightarrow n_3$ at cost α_2^f.

We solve the market clearing problem for this setting under different scenarios that capture different bidding values (see Table S1). We make the following observations:

- In scenario I, a maximum social welfare of $7{,}000$ USD is achieved and we can see that all players have a non-negative profit values (in agreement with Theorem 1). The supplier and the transportation providers have a profit value of zero. This is because the nodal price at node n_1 is same as the bid made by the supplier and the difference in the prices at nodes n_1 and n_2 is the same as the bid of the transportation provider over link $n_1 \rightarrow n_2$ (the same behavior is observed along path $n_1 \rightarrow n_3$). The profit made by the transportation provider is thus zero. The profit of the consumers is positive, indicating that the cleared prices are lower than their bids. It can be easily verified that all the clearing prices satisfy the bounds of Theorem 4. We also highlight that the clearing prices for waste are different in all nodes (the prices are balanced by clearing to ensure that all players have a non-negative profit).

- In scenario II, the bid made by the second consumer is reduced. In this case, we obtain similar results to those of the previous setting but we note that no waste is allocated to the second consumer. This is because there is no economic incentive to transport the waste between node n_1 and n_3. In particular, the difference in the clearing prices between n_1 and n_3 is lower than the bid of the transportation provider along that path. From this setting it is easy to verify that revenue adequacy holds (Theorem 3). In particular, the consumer (connected to node n_2) pays $3.5 \times 3{,}000 = 10{,}500$ USD for the waste provided, the supplier (connected to node n_1) gets paid $1.5 \times 3{,}000 = 4{,}500$ USD, and the transportation provider (for the link $n_1 \rightarrow n_2$) gets paid $(3.5 - 1.5) \times 3{,}000 = 6{,}000$ USD. Consequently, there is no money lost in the system.

- In scenario III, the supplier bid is increased. In this case, no player is cleared (the market is dry and thus the social welfare is zero). The difference in the bidding costs between nodes n_1

and n_2 and between n_1 and n_3 are lower than the bids of the transportation providers along the corresponding paths. These results illustrate how spatial interdependencies between waste values and transportation costs are captured by the market framework.

4.2 System with Negative Bidding Costs

We now consider a market setting (labeled as B) that involves negative bidding costs. This setting consists of one waste supplier located in node n_1 (e.g., a WWTP generating sludge waste) with supply capacity $\bar{s}_1 = 5{,}000$ tonne and bidding cost α_1^s. The sludge can be used for land application and is requested by a consumer (e.g., a farmer) located at node n_2 with bidding cost α_1^d. A transportation provider offers service along path $n_1 \rightarrow n_2$ with bidding cost α_1^f. In this setting, the bidding supply and demand costs are allowed to be negative. A negative supply bid indicates that the WWTP is willing to pay the consumer to dispose of the sludge. Similarly, the negative demand bidding cost represents that the customer requests to be paid in order to accept the waste and apply it to its land. The results obtained under different bidding values are shown in Table S2. In scenario I we note that, the supplier makes a profit since it ends up paying less to the market (than it's bid value) to get the waste processed. Moreover, we see that neither the consumer nor the transportation provider make a profit. In scenario II we note that, when the consumer submits a negative bid, the supplier still makes a profit (but this is cut in half compared to scenario I). This captures the fact that now a payment needs to be made to the consumer for it to take the waste (so that revenue adequacy holds). This is also reflected by the fact that the price at node n_2 is negative (and thus can be interpreted as a tipping fee). We also note that, the payment made to the consumer makes its profit zero (the consumer is not affected by taking the waste). Consequently, the supplier has an incentive to provide its waste (even when paying for it) and the consumer is not affected by this. This non-intuitive behavior is the result of having a coordinated clearing mechanism that maximizes the social welfare and adjusts the prices in order to ensure that all players benefit from the market. In scenario III we note that, when the consumer increases the magnitude of its negative bid, no player is cleared (the market is dry). This is because the difference in the supply and demand bids is lower than the bidding cost of the transportation provider (there is no incentive to transport waste).

4.3 System with Transformation

We now consider a market setting (labeled as C) with waste transformation. This setting is sketched in Fig. S1. The system comprises a supplier providing a waste product p_1 at node n_1 with a maximum capacity $\bar{s}_{1,p_1} = 10{,}000$ tonne and bidding cost α_1^s. The transformation provider is located at node n_2 has a maximum processing capacity of $\bar{\xi}_1 = 8{,}000$ tonne of waste p_1 and a bidding operating cost α_1^ξ. This transformation provider converts one unit of product p_1 to 0.01 units of a high-value product p_2 and 0.99 units of a low-value product p_3. A bid is put into the market for product p_2 at node n_3 by a consumer with capacity $\bar{d}_1$ and bidding cost α_1^d. A bid is put into the market for product p_3 at node n_4 by a consumer with capacity $\bar{d}_2$ and bidding cost α_2^d.

The results of this market setting are summarized in Table S3. In scenario I, we can see that there exists an incentive for the transformation provider to create product p_2 from product p_1 and this results in a large profit. This is manifested in a positive transformation price π_1^{ξ}, which is given by $3{,}495 \times 0.01 - 7 \times 1 - 4 \times 0.99 = 23.99$ USD. We also note that this transformation price is higher than the processing bid cost of 20 USD (consequently, the profit is positive). Interestingly, none of the other market players make a profit in this setting (they are simply not affected by the transaction). In scenario II, the demand bid for p_2 from the first consumer decreases and the market becomes dry (this is because the transformation price is now 19.99 USD (which is lower than the bid). These results illustrate how interdependencies between waste and product values and transformation costs are captured by the market framework.

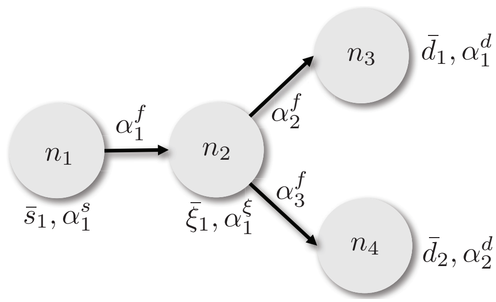

Figure S1: Sketch of market setting C

Table S1: Clearing results for market setting A

Scenario	**Bids** (USD/tonne)					**Welfare** (USD)	**Profits** (USD)				**Prices** (USD/tonne)
	α_1^s	α_1^d	α_2^d	α_1^f	α_2^f	φ	ϕ_1^s	ϕ_1^d	ϕ_2^d	ϕ^f	$[\pi_{n_1}, \pi_{n_2}, \pi_{n_3}]$
I	1.5	5	6	2	4	7,000	0	4,500	2,500	0	1.5, 3.5, 5.5
II	1.5	5	5	2	4	4,500	0	4,500	0	0	1.5, 3.5, 5.0
III	3.5	5	5	2	4	0	0	0	0	0	3.5, 5.0, 5.0

Table S2: Clearing results for market setting B

Scenario	**Bids** (USD/tonne)			**Welfare** (USD)	**Profits** (USD)			**Prices** (USD/tonne)
	α_1^s	α_1^d	α_1^f	φ	ϕ_1^s	ϕ_1^d	ϕ_1^f	$[\pi_{n_1}, \pi_{n_2}]$
I	-6	$+0.0$	5	5,000	5,000	0	0	$-5.0, +0.0$
II	-6	-0.5	5	2,500	2,500	0	0	$-5.5, -0.5$
III	-6	-1.5	5	0	0	0	0	$-6.5, -1.5$

References

[1] Dairy industry contributes $43.4 billion to Wisconsin's economy. *University of Wisconsin-Extension available at* https://fyi.uwex.edu/extensioninthenews/2015/01/26/dairy-industry-contributes-43-4-billion-to-wisconsins-economy-2/, 2015. [Online; accessed 13-July-2018].

Table S3: Clearing results for market setting C

Scen.	**Bids** (USD/tonne)	**Welfare** (USD)	**Profits** (USD)	**Prices** (USD/tonne)
	$[\alpha_1^s, \alpha_1^d, \alpha_2^d, \alpha_1^\xi]$	φ	$[\phi_1^s, \phi_1^d, \phi_2^d, \phi^\xi]$	$[\pi_{n_1,p_1}, \pi_{n_3,p_2}, \pi_{n_4,p_3}, \pi_{n_2,p_1}, \pi_{n_2,p_2}, \pi_{n_2,p_3}]$
I	$[2, 3500, 1, 20]$	$31,920$	$[0, 0, 0, 31920]$	$[2, 3500, 1, 7, 3495, -4]$
II	$[2, 3000, 1, 20]$	0	$[0, 0, 0, 0]$	$[1, 3000, 1, 6, 2995, -4]$

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