Infrastructure Support for Bioenergy Development in Cities

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Abstract Worldwide, bioenergy production is increasing. However, there is still a lack of understanding of the types of infrastructural modifications necessary to support further bioenergy development in ways that are both cost effective and environmentally sustainable. This paper provides an overview of the infrastructure support crucial for enabling large-scale bioenergy production in cities. Three waste-to-bioenergy pathways to produce biodiesel from waste oils, syngas from plasma gasification of municipal solid waste (MSW), and bioenergy from algae are reviewed. (i) To produce biodiesel from waste oils, a cost-effective feedstock collection system is key as feedstock cost, including transportation cost, is the single largest contributor to total cost. (ii) To promote the production of syngas from MSW by plasma gasification, a decentralized approach is recommended in the near to medium term. This is because at present, there is still little experience operating large MSW plasma gasification plants. A decentralized approach creates opportunities for public-private partnerships, leading to investments to gain operational experience. Soft infrastructure in the form of a well-developed recycling program or legislation is also necessary to ensure the gasification does not compete with recycling for recyclables. (iii) To produce bioenergy from algae, two infrastructures are vital. The first is infrastructure to integrate wastewater treatment and algae cultivation with nutrients and carbon dioxide recycling. The second is infrastructure to create large surface areas from sides of buildings and/or rooftops that are well exposed to sunlight for algae growth. Provided these infrastructures are in place, the three pathways, combined, have the potential to supply up to 12–16 % of

Hong Kong's electricity demand if converting the energy products from the pathways to electricity. Further, the pathways create new interdependencies between the waste and energy sectors. The interdependencies, while synergistic, could lead to new vulnerabilities such that a failure of one sector will cause a failure in the other as well. Care must be taken when designing systems to minimize this.

Keywords Bioenergy · Cities · Waste-to-energy · Waste oils · Plasma gasification · Algae cultivation · Algae wastewater treatment

Introduction

Production of bioethanol in the USA, presently the largest producer and consumer of bioethanol in the world, increased nearly ten-fold from 2000 to 2011, from 17,000 to 145,000 m³/day [1]. Production of biodiesel has also increased; globally, in 2011, it stood at 64,000 m³/day, up from 2,400 m³/day in 2000 [1]. Bioenergy in the form of electricity is also quickly proving to be viable. In 2010, 1.5 % of the world's electricity production was from bioenergy, and by 2050, there is potential for this percentage to increase to 7.5 % [2].

Despite these increases, there is still no adequate understanding of the types of infrastructural modifications necessary to fully support bioenergy development. While several authors [3, 4•, 5–7] have addressed various aspects of the problem, a comprehensive understanding that is both holistic and quantitative is still lacking. The fact that bioenergy creates new interdependencies between multiple systems (such as biorefining, transportation, water, and agriculture) of very different natures further complicates the problem [4••].

This paper seeks to fill some of this gap in understanding by providing an overview of the infrastructure support crucial

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for enabling large-scale bioenergy production in cities. Slightly more than half of the world's population live in cities [8], accounting for over 60 % of the global energy consumption [9]. By maximizing bioenergy production in cities, production is maximized at the point of consumption, thus reducing transport costs, both financial and environmental [10–12]. These costs are not insignificant given the growing global bioenergy market [13] giving rise to large-scale transportation of biomass and biofuels from countries with greater supplies to countries with limited supplies but greater demands.

Additionally, bioenergy production in cities provides unique opportunities for converting waste to energy. This shifts the historical view of waste as a problem to it as being a resource, leading to more sustainable urban waste solutions. Bioenergy can be produced via pathways that are well established (e.g., incineration of municipal solid waste [MSW] to produce heat and electricity, and anaerobic digestion of sewage sludge to produce methane) and pathways that are less common or less well understood but offer promises for the future. In this review, focus is given to the latter, including processes to turn waste oils to biodiesel, MSW to syngas, and algae to solid, liquid, and gaseous fuels. To illustrate certain points, some of the discussion is made in the context of Hong Kong (HK), a metropolis of 7.16 million.

Biodiesel From Waste Oils

Yellow grease is used oil from cooking that has not been washed down the drain and thus, is uncontaminated by wastewater. Brown grease is grease recovered from grease traps that has been in contact with wastewater. Increasingly, these waste oils are being recovered from restaurants, bakeries, and food processing plants, and converted to biodiesel as in HK [14] and San Francisco [15].

HK produces 480 Mg/day of brown grease [16], most of which is water and only about 3.75 % is useful grease [17]. Further, HK produces 79 Mg/day of yellow grease assuming a basis of 0.011 kg/day per person [18]. Combined, these provide 97 Mg/day of waste oils that could potentially be converted to biodiesel to satisfy 2.2 % of the city's demand for diesel for road transportation [19]. (Alternatively, co-firing the waste oils in a power plant generates 17.4 MW of electricity assuming a heating value of 41 MJ/kg and conversion efficiency of 38 %. This is equivalent to 0.35 % of HK's total electricity consumption in 2012 [20].)

Biodiesel from waste oils offers an alternative source of fuel that does not require extensive engine modifications, if at all, to use in diesel engines [21]. It creates an incentive for recovering waste oils that would otherwise be landfilled or discharged to sewers to eventually block pipes. It also leads to air quality improvements as it is generally cleaner burning

than petroleum-derived diesel (but may lead to higher nitrogen oxide emissions) [22–24].

The first infrastructure requirement of a waste oils-to-biodiesel program is a collection system. Yellow grease is usually stored in drums that when full, are transported by truck to a final destination for processing to biodiesel. Brown grease collected upon emptying of grease traps and interceptors is usually transported almost immediately, e.g., by tankers, for pretreatment to dewater the grease and remove contaminant solids. The Grease Trap Waste Treatment Facility (GTWTF) [17] in HK is an example of a facility for such pretreatment.

The GTWTF is installed with treatment units to purify the grease by screening, air flotation, and centrifugation. It is also fitted with flocculation and biological treatment units to treat wastewater arising from the grease purification process. It is a centralized facility and is situated on the same compound as the city's largest solid waste transfer station. This gives it greater economy of scale because the wastewater treatment units clean not only wastewater from the grease purification but also wastewater from solid waste transfer operations. Furthermore, solids from the grease purification are sent to a nearby landfill using the same loading facilities and transport as for sending other solid wastes from the transfer station. Similarly, the weighbridges and terminals used to receive tankers carrying brown grease are the same as for receiving garbage trucks.

Waste oils are most commonly converted to biodiesel by transesterification [25], a catalytic process where triglycerides in the waste oils react with an alcohol, usually methanol, to yield biodiesel and glycerol. For every 1 L of biodiesel, 0.126 kg of glycerol is produced [26] that may be sold to offset some of the cost of biodiesel production by about 6–36 % [25, 27, 28]. However, in recent years, rising biodiesel production has resulted in an oversupply of glycerol, causing drastic declines in glycerol price [26, 29], though it can be expected to recover in due time as the worldwide demand for glycerol grows [30].

The greatest single factor affecting the economic feasibility of biodiesel production from waste oils is the feedstock cost, accounting for 20–50 % of total cost for a 8,000 Mg/year refinery [25, 27], or even 70–80 % of total cost for larger refineries [27]. Feedstock cost is partly governed by transportation cost that can be reduced by optimally routing collection vehicles. This is as demonstrated by Araujo et al. [31] using a mixed integer linear model applied to an urban area in Brazil. For the case study, assuming a single refinery at a fixed location, the authors found transportation cost to be at minimum, US\$0.11/L. In comparison, total cost was found to be on average, US\$0.73/L. Transportation cost can be further reduced by optimally locating multiple biorefineries and transportation hubs, also using mixed integer programming [32]. Hubs are transshipment points at intermediate locations for

pretreating waste oils and consolidating loads, much like the GTWTF described above.

To summarize, the technology to recover yellow and brown grease to convert to biodiesel (or co-fire to produce electricity) is well developed. At current conditions, to do so is both economically and energetically feasible provided processing facilities are built large enough for economy of scale. Feedstock cost, including transportation cost, is the single largest contributor to total cost. Thus, the infrastructures to further improve the feasibility of the process, thereby increasing its attractiveness to private investors, are those that reduce feedstock cost. A centralized facility to collect and purify brown grease, such as the GTWTF in HK, is one such infrastructure. Intermediate transportation hubs to optimize collection vehicle routing are another such infrastructure.

Syngas From Municipal Solid Waste

MSW is another potential source of bioenergy in cities. One well-established MSW-to-energy pathway is incineration to produce heat and electricity. However, incinerators are difficult to locate. There is often great opposition to new incinerators from local communities owing to the perception that they emit furans and dioxins that are highly toxic to humans. Incinerators are also expensive and require a high degree of expertise to operate.

With recent developments, there are now other options, namely gasification to produce syngas, and hydrolysis followed by fermentation to produce bioethanol. Between them, gasification is the more flexible. The syngas that it produces is an intermediate product that can be further processed into other chemicals including biodiesel and bioethanol. It can also be burned to create electricity. Conversely, bioethanol from hydrolysis and fermentation is a single end-product with limited application. Further, if employing the latest technology based on plasma torching, gasification can accept mixed MSW as feedstock, eliminating the need for expensive sorting. However, the same is not true for hydrolysis and fermentation where the specific chemicals, enzymes, and bacteria to be used vary with feedstock type.

From a comparison [33] of the life-cycle greenhouse gas (GHG) emissions, fossil fuel consumptions, and water footprints of producing bioethanol via gasification and via hydrolysis and fermentation for a variety of lignocellulosic feedstock, including waste paper, the latter was found to be advantageous in terms of GHG emissions and fossil fuel consumption but only slightly so. However, it has a water footprint that is significantly greater. Thus, for this reason and for the greater flexibility gasification provides, gasification is deemed the more promising.

In standard gasification, organic materials are converted to syngas in an oxygen-limited environment under temperatures

of 750–1500 °C. (Syngas is a mixture of carbon dioxide [CO₂] and mostly hydrogen and carbon monoxide.) A small amount of oxygen is supplied, just enough to combust a portion of the feedstock to provide sufficient heat for the actual gasification process. Plasma gasification is similar to standard gasification but occurs under even higher temperatures, 4000–7000 °C, made possible by additional heat from plasma arc torches.

See Table 1 below for a comparison of the net electricity productions of the two technologies (assuming the syngas produced is used to generate electricity) and incineration, as well as the temperatures under which they operate. Plasma gasification has a net production that is highest, followed by standard gasification, then incineration. Assuming a lower heating value of 13 MJ/kg, the efficiencies in the table suggest plasma gasification to have the potential to produce, on average, 370 MW of electricity from the 9278 Mg/day of MSW [16] sent to landfills in HK, and standard gasification to produce 262 MW. The former is enough to supply up to 7.5 % of the total electricity consumption of the city for 2012 and the latter 5.3 % [20]. In the future, this potential can be further improved by integrating fuel cell technology [34, 35] as the technology matures.

For electricity generation, plasma gasification is the most promising, but at present, there is still a lack of experience building and running large plasma gasification plants. Because of the relative novelty of the technology, the plants that are in operation have relatively small capacities that are far from the scale required for MSW disposal in large cities. Two early commercial facilities are the 24 Mg/day plant in Mihama-Mikata, Japan commissioned in 2002, and the 220 Mg/day plant in Utashinai, also in Japan, commissioned in 2003 [36]. (The plant in Utashinai, a rural area, closed in 2013 because of insufficient feedstock [37].) At the time of writing, larger plants are under construction such as the two facilities in Teeside, UK designed to each accept 1000 Mg/day of sorted MSW [38]. The two facilities will be among the first, if not the first, of their size.

Because of this lack of a proven record for large plants, in HK, the government has explicitly rejected the building of a MSW plasma gasification plant citing concerns of reliability and scalability [39]. Instead, it opted for a 3,000 Mg/day incinerator amid great resistance from the local community [39, 40]. The HK government's conservative stance is most likely than not typical of most other governments around the world. Thus, in the short to medium term, to promote energy production from plasma gasification of MSW, a decentralized approach, as compared with a centralized one, is perhaps prudent.

A decentralized approach is one where there exist multiple small plants. This is opposed to a single or few large plants as is often the case of incinerators that are usually developed as large centralized facilities for greater economy of scale. Cost figures [41] suggest that plasma gasifiers with capacities as

Table 1 Incineration, standard gasification and plasma gasification operating temperatures, net electricity productions, and net electricity production efficiencies

Technology	Temperature (°C)	Net Electricity Production (kWh/Mg) ¹	Net Electricity Production Efficiency (%)	References
Incineration	550–1200	100–650	6.5–21	(41, 71–74)
Standard gasification	750–1500	641–752	17–20.5	(41, 71, 73)
Plasma gasification	4000–7000	897–1270	23–30	(41, 72, 75, 76)

¹ kWh per Mg municipal solid waste or per Mg refuse-derived fuel

small as 300 Mg/day can break even assuming a tipping fee, electricity price, and green subsidy of US\$39/Mg, US\$0.065/kWh, and US\$0.02/kWh, respectively. Furthermore, decentralization creates opportunities for private-public partnerships, providing an incentive for private firms to invest in research to further bring down costs while improving performance, thus leading to even smaller capacities being profitable. Decentralization also reduces transportation costs.

Like incineration, gasification competes with recycling for waste. If gasification is adopted without first there being an effective recycling program, gasification could lead to a disincentive for recycling to become widespread. Specifically, it could lead to less paper, plastics, and kitchen waste being recycled because of their high calorific values. (However, it could lead to more recycling of metals and glass, which have zero calorific value and for optimal gasifier performance are best to be sorted out in a pretreatment stage.) To prevent gasification from diverting waste away from recycling, strict legislation mandating recycling, not unlike San Francisco's Mandatory Recycling and Composting Ordinance [42], may be necessary. Alternatively, a gasification tax, similar to an incineration tax, may be considered though such a tax is likely to be ineffective if cross-border transport of waste is not controlled to prevent the channeling of waste to incinerators or gasifiers in other jurisdictions with lower or zero tax rates [43, 44].

In summary, of several methods to convert MSW to bioenergy, plasma gasification is the most promising for its ability to accept mixed unsorted waste and also its higher feed-to-energy conversion efficiency. However, at present, there is very little, if not zero, long-term experience operating large MSW plasma gasification plants. Thus, in the near future, to gain valuable operational experience, decentralization involving private-public partnerships is recommended to accelerate investments and infrastructure expansion. It is also necessary the concurrent development of soft infrastructure in the form of effective legislation or an extensive recycling program to ensure the long-term sustainability of MSW plasma gasification by preventing its consumption of recyclables.

Bioenergy From Algae

Algae are fast-growing aquatic plants found in almost all places under a wide range of conditions. Algae are composed of lipids, carbohydrates, and proteins. Much of the relevant literature is focused on converting the lipids to biodiesel by transesterification [45, 46]. There are also studies on converting the carbohydrates to bioethanol by fermentation [47], and the entire algal biomass to a variety of energy products by direct combustion [48, 49], hydrothermal gasification [50, 51] and liquefaction [50, 52••], and anaerobic digestion [53, 54].

A key advantage of algae over other bioenergy crops is their higher areal productivity. For an area of land, algae have the potential to produce up to 340–800, 130–300, and 10–20 times more oil than corn, soybeans, and oil palm, respectively [46]. Furthermore, land for algae need not be arable, which eliminates, at least partially, any competition between algal energy and food crops. Algae's ability to thrive in saline and brackish waters (and not just freshwater) is another advantage.

In urban areas with large flows of wastewater, there exist opportunities to integrate algae cultivation and wastewater treatment. Algae have been shown to be efficient in removing nitrogen, phosphorus, and oxygen-demanding substances from municipal wastewater. See Table 2 for the results of experiments on using algae for treating municipal wastewater in open pond systems and photobioreactors (PBRs). As can be seen, algae are suitable for all stages of wastewater treatment, i.e., primary, secondary, and tertiary. Algae may also be used for treating dewatered sludge centrate.

Integration reduces overall cost and energy use [55–57] by replacing freshwater with wastewater as the algae culture medium, and by minimizing the need for chemical fertilizers for algae growth (which can account for as much as 50 % of life-cycle energy use and GHG emissions from algae cultivation [58]). Integration also reduces the energy requirements of wastewater treatment as the more the nutrients are removed by algae, the less there are to be removed by conventional energy-intensive methods. Under optimistic assumptions of algae productivity and with the right infrastructure design, it is possible, theoretically at least, for algae to turn wastewater

Table 2 Biomass productivity, lipid content, and chemical oxygen demand (COD), total nitrogen (TN), ammonia (NH₄-N), total phosphorus (TP), and phosphate (PO₄-P) removal efficiencies of algae in wastewater in open pond systems and photobioreactors, with and without air and/or carbon dioxide (CO₂) injection, given hydraulic detention time

Wastewater Type	Biomass Productivity (g/m ² /day)	Algae Lipid Content (%)	COD Removal (%)	TN Removal (%)	NH ₄ -N Removal (%)	TP Removal (%)	PO ₄ -P Removal (%)	Detention Time (days)	Air, CO ₂ Injection	Source
Open Pond Systems										
Settled raw wastewater	14.8	–	38	57	–	32	–	4–8	–	(77)
Settled raw wastewater	12.7	–	35	73	–	44	–	7–10	–	(77)
Primary settling effluent	–	–	68–80	–	92–94	–	71	4–8	–	(78)
Secondary settling effluent	12.0	10	–	61	–	91	–	10	Air	(55)
Secondary settling effluent	8.26	21	–	65	–	59	–	10	–	(79)
Photobioreactors										
Primary settling effluent	~4.13	9.0	–	–	> 99	–	> 99	3	CO ₂ -air	(60)
Primary settling effluent	~1.58	9.3	–	–	84	–	> 99	3	Air	(60)
Secondary settling effluent	10.9	–	98	88 ¹	–	–	65	9	–	(80)
Secondary settling effluent	21.8	21	–	90	–	87	–	5	Air	(79)
Dewatered sludge centrate	27.0	5.5	70	61 ¹	–	61 ²	–	4	–	(81)
Dewatered sludge centrate	19.7	5.5	70	45 ¹	–	53 ²	–	4	CO ₂	(81)
Synthetic wastewater	5.1	–	–	84	–	51	–	15	Air	(82)

¹ Value for total Kjeldhal nitrogen² Value for total soluble phosphorus

– Indicates unavailable data

treatment facilities from net energy consumers to net producers [52•, 59•].

Carbon-to-nitrogen and carbon-to-phosphorus ratios in municipal wastewater are generally lower than in algae biomass [60]. This limits algae productivity and nutrient removal efficiencies. Injecting a mixed stream of carbon dioxide CO_2 and air into the algae-wastewater culture overcomes this limitation (as the results by Woertz et al. [60] in Table 2 prove), and at the same time, sequesters CO_2 . Algae have the potential to remove as much as 2,500 mg/L/day of CO_2 depending on the algal strain, reactor design, light availability, pH, and other growth conditions [61, 62]. This corresponds to up to 60 % CO_2 removal from influent streams consisting of 0.03–60 % CO_2 [61].

Thus, even greater synergy is possible if integrating wastewater algae cultivation with sequestration of CO_2 from power generation. Menger-Krug et al. [59•] described a process to recycle flue gas through an algae culture in wastewater. The flue gas comes from combusting methane from anaerobically digesting sewage sludge and algae biomass. Nutrient-rich dewatering centrate is also recycled back to the algae culture. By modeling the mass and energy balances of the system, the authors demonstrated the potential of algae to improve the energy return of a typical municipal wastewater treatment plant from 0.3 to 0.62, assuming limited CO_2 recycling, and up to 1.01, assuming full CO_2 recycling. (Energy return is the amount of energy generated for every unit of energy consumed. A facility with a return less than one is a net energy consumer, but a net producer with a return more than one.)

Zhou et al. [52•] proposed an alternative process called the “Environment-Enhancing Energy” (E^2 -Energy) process to recycle CO_2 and nutrients for growing algae in wastewater. The process involves converting sewage sludge and algae biomass to bio-oil, a substance resembling crude oil, via hydrothermal liquefaction. This produces CO_2 and nutrient-rich wastewater that are subsequently recycled back to the algae culture. The authors developed a mass and energy balance model parameterized by experimental values to simulate the performance of the system, and found it capable of biomass and biofuel yields up to ten times greater than in a comparable system without recycling. E^2 -Energy has the potential to be a net energy producer with an energy return up to 2.8.

Algae may be cultivated in open ponds or PBRs. Because of their simple designs, open ponds are relatively cheap to build and operate, and have energy demands that are minimal. In contrast, PBRs have more complex designs and are usually closed systems to allow for greater control of operating variables to optimize productivity. However, they are expensive and require larger amounts of energy to operate. Open ponds have been shown to be viable, tubular PBRs unviable, and flat-plate PBRs potentially viable depending on operating conditions [63–65]. Even though research is currently underway to improve PBR performance [66], for the near future, it

is likely for any commercialization of algal energy (without the co-production of high-value non-energy products) to involve open ponds. Both the processes by Zhou et al. [52•], i.e., E^2 -Energy and Menger-Krug et al. [59•] described above assume open ponds.

Open ponds, however, require land that may not be available. To divert all 2.69 million m^3 /day of wastewater generated in HK [67] towards open pond algae cultivation for producing bio-crude oil using the E^2 -Energy process, 52 km^2 of land is needed. This is assuming a hydraulic detention time of 10 days [68] and a pond depth of 0.5 m. This is equivalent to 4.7 % of the total area of HK or four times the area of HK International Airport. In HK, where land prices are among the highest in the world, it is not likely practicable to allocate this large an area to algae cultivation.

Nonetheless, the potential of algae as a major energy source cannot be ignored. Zhou et al. [52•] estimated an E^2 -Energy plant treating 1,000 m^3 /day of municipal wastewater to have the potential to produce 512–990 kg/day of bio-crude oil with a higher heating value of 38 MJ/kg. Thus, from HK’s 2.69 million m^3 /day of wastewater, there is the potential to produce 1,330–2,570 Mg/day of bio-crude oil. Assuming an efficiency of 38 %, firing this bio-crude oil yields 205–396 MW of electricity, enough to meet 4.2–8.1 % of the city’s total electricity demand [20].

Thus, to realize the full potential of algae in a highly dense environment such as HK, it may be necessary to use PBRs despite their generally higher cost and energy use. Although PBRs do not necessarily lead to greater areal biomass productivities (see Table 2), with PBRs, there is more flexibility to make use of inclined or vertical surfaces, allowing for the use of rooftops and sides of buildings, thus mitigating the problem of land availability. At the same time, algae PBR systems have the potential to provide insulation, shading, and noise abatement to buildings. The Bio Intelligent Quotient demonstration building [69], recently showcased in Hamburg, Germany in April 2013, is an example of a building incorporating algae in PBRs, in this case, flat-plate PBRs. Another example is a high-rise building in the La Defense business area near Paris [70], which is also a demonstration project and with flat-plate PBRs on its sides.

As a summary, to support the development of bioenergy from algae in the urban context, two infrastructures are vital. First is infrastructure to integrate wastewater treatment and algae cultivation. This includes equipment to generate power onsite from the cultivated algae, and to recycle the resulting CO_2 emissions and nutrient-rich wastewater back to the algae culture in the manner of the E^2 -Energy process [52•]. At the current state of technology, it is only with this that it is possible to have a significant enough biomass productivity without a prohibitive need for freshwater or chemical fertilizers. The second key infrastructure is infrastructure to create large surface areas from sides of buildings and/or rooftops that are well

exposed to sunlight for algae growth. While there are now at least two demonstration buildings (one in Germany and the other in France) showing how PBRs can be integrated into the structure of a building for this purpose, the cost of doing so is as yet uncompetitive and more research is essential.

Implications and Challenges

Large-scale bioenergy production from urban waste integrates sectors in ways that are novel and yet to be fully understood. Even though there are existing links between the solid waste and energy sectors from MSW incineration, new links can be expected as other waste-to-energy pathways, including the three discussed in this paper, advance in technology and popularity. Consider for example, new links between wastewater treatment and energy production that wastewater-based algal bioenergy systems create. Such systems also create new links between water supply and energy production as water supply affects wastewater flows that, in turn, affect algae cultivation. This is especially so with onsite water reuse options such as gray water recycling that, by decentralizing wastewater treatment to some extent, significantly reduce flows to main sewers.

A complete understanding of the potential of urban bioenergy production requires a holistic systems perspective that is at present, still absent in the literature. A systems view is essential for answering questions of cost and energy savings, short- and long-term operations, and optimal strategies for infrastructure development considering existing facilities. New model formulations requiring new sets of data are required. For large nonlinear discontinuous systems with thousands of discrete and continuous variables, improved methods of solution and optimization may also be required.

City planners must also be aware of possible hazards stemming from the stronger connection, or interdependency, between the waste and energy sectors. Using a hypothetical case study of an agricultural biofuel system with subsystems of biorefining and transportation, Ng and Cai [4••] showed interdependency to have an effect on system reliability and vulnerability. (As described by the authors, system reliability is the probability of either or both subsystems failing, while system vulnerability is the aggregate of the extents of failure of the two subsystems.) The authors also showed the locations of facilities to influence interdependency, hence reliability and vulnerability. Generally, it was found that a centralized system (compared with a comparable decentralized one) is more likely to have both subsystems failing at once, but the sum of their individual failures to be less severe. In other words, a centralized system was found to fail more frequently, but with smaller sums of failure.

It is uncertain how much of the findings by Ng and Cai [4••] applies to an urban bioenergy system incorporating

waste oils, MSW, and algae in wastewater. Nonetheless, they highlight the importance of more understanding on how infrastructure integration and design can lead to new weaknesses if not carried out with caution. Ideally, an integrated waste-to-energy system would be one where neither subsystem is overly dependent on the other such that a failure of one will cause the other to fail as well. However, this may require redundancies in the system. More research is needed to identify specifically how this is possible without incurring excessive additional costs.

It is also uncertain how differences between cities might affect the potential of producing bioenergy from urban waste. One factor to consider is population density. HK has one of the highest population densities in the world. Similarly, the densities of a number of cities in China and India are reaching that of HK, even surpassing it. Conversely, cities in places such as Australia and the USA, in general, have much lower densities. A higher density means lower transportation costs and greater economies of scale that lower the costs of facilities and certain operations. At the same time, a higher density also means scarcer land resources that could make land unavailable for the development of facilities at optimal locations. This is especially true in the case of producing algal bioenergy from wastewater, which requires large surface areas to grow the algae.

Conclusions

With technological advances, there is new potential to convert waste to bioenergy in cities. Three waste-to-bioenergy pathways are reviewed. As summarized in Table 3, for the case of HK, these pathways, together, have the capacity to supply up to 12–16 % of the city's electricity demand.

Each pathway requires a different set of infrastructures to be developed or improved to meet its full potential. To produce biodiesel from waste oils is already commercial and in many places, cost feasible; to make it even more economically

Table 3 Three waste-to-energy pathways for producing bioenergy in cities at different stages of development, and with the potential to meet different percentages of Hong Kong's total electricity demand

Pathway	Developmental Stage	Energy Potential as % of Hong Kong's Total Electricity Demand
Recovery of waste oils	Commercial	0.35 ¹
Plasma gasification of municipal solid waste	Demonstration/early commercial	7.5
Algae cultivation in wastewater	Experimental/demonstration	4.2–8.1

¹ Waste oils can also be converted to biodiesel to satisfy 2.2 % of Hong Kong's demand for diesel for road transportation

attractive, a well-planned feedstock collection system is key. As for MSW plasma gasification, currently, there lacks long-term experience building and operating large MSW plasma gasification plants. To gain this experience, public-private partnerships to first develop relatively small, then gradually larger and larger facilities are recommended. Legislation or an extensive recycling program is also recommended to prevent the gasification from competing with recycling for recyclables. More fundamental research is still needed before it is possible to produce algal bioenergy from algae-wastewater systems on a large scale. In particular, more research is needed on integrating wastewater treatment and algae cultivation facilities, and also on developing cost-effective low-energy PBRs for growing algae on vertical and inclined surfaces. If infrastructures are developed to support the production of bioenergy from urban waste, the interdependencies they create between the waste and energy sectors, and their implications, must be well understood.

Ideally, in the not-too-distant future, as the technologies to support the three waste-to-energy pathways mature, more and more cities will adapt their current waste management practices and infrastructures to produce bioenergy for more sustainable operations. To do so will necessitate opposing convention, which will require political will, in addition to sound technical understanding. Appropriate economic and public policies are also essential to drive change in the desired direction by either mandating the change or providing economic incentives to manipulate market forces.

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