An assessment of Greenhouse Gas (GHG) emissions of two organic waste processing options for UBC

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An assessment of Greenhouse Gas (GHG) emissions of two organic waste processing options for UBC

A UBC SEEDS Project

CEEN 523 Term Paper

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EXECUTIVE SUMMARY

In our study, we evaluate two food waste processing options for the University of British Columbia for emissions of greenhouse gasses. We considered an on-campus option based on the existing UBC in-vessel aerobic composting system, and an off-campus option based on an anaerobic digestion system located in Richmond, BC that generates energy from biogas.

We found that of the two options we considered, the off-campus anaerobic digestion option had net 52 tonnes lower CO2e emissions than the on-campus option based on the emission factors and assumptions we used. We found that emissions from food waste diverted to landfill for the on-campus option and carbon stored in soil from compost were the most significant factors affecting emissions. We further found that emissions related to transportation were minor relative to other emissions as were emissions from electricity used for the on-campus facility.

We conclude that both options provide significant reductions relative to sending food waste to regional waste disposal facilities. We recommend that UBC consider the benefits of including a waste sorting system to reduce or eliminate rejected food waste in any future processing options implemented by UBC.

Further work could focus on completing energy and mass balances for the off-campus option, and determining associated emissions. A full life cycle analysis could consider the fate of all campus food waste (not just waste diverted to organic processing facilities) and evaluate a range of human health and environmental impact factors.

INTRODUCTION

As University of British Columbia prepares to implement its Zero Waste Plan, organic waste diverted to composting is expected to triple over the next 3 – 5 years, increasing to 1300 tonnes annually by 2017 (SEEDS 2013). This expansion will likely exceed the capacity of UBC's existing compost system and this, along with operational issues, has led UBC to consider alternative options including expansion of the existing system or sending some or all food scraps for off-campus processing (SEEDS 2013).

Project Objective

The objective of this project is to evaluate two organic waste processing options for UBC. One option is based on the existing on-campus aerobic composting facility, the second option is based on sending food waste off-campus to the Harvest Power biogas facility in Richmond, BC.

Option Descriptions

The on-campus option utilizes an 'in-vessel' fully-enclosed system which allows for a controlled, accelerated, aerobic composting process. The UBC facility, the first of its kind at a Canadian university, is capable of processing up to 5 tonnes/day and generates raw compost in 14 days (this excludes maturation time) [1]. It includes a negative aeration biofiliter system.

The off-campus option is a biogas and composting facility that is based on an anaerobic digestion (AD) system that generates methane and other gasses. It utilizes a high solids, mesophilic, multi-stage batch process to process food and landscaping organic waste[2]. It also includes an aerobic composting stage to process solids from the anaerobic stage and other organic waste. The aerobic stage includes a negative aeration biofiliter system. The Harvest Power facility is capable of processing up to 30,000 tonnes/year and generating up to 2 MW of power through a combined heating and power(CHP) system[2].

The off-campus option also includes a proposed sorting facility operated by Earth Renu Energy Corp, located on Annacis Island. The sorting facility would remove contamination from UBC food waste, ensuring food wasted delivered to the Harvest Power facility is nearly contamination free.

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[1] UBC in-vessel compost system description.
[2] Harvest Power biogas facility description.

Project Scope

The focus of our evaluation is on greenhouse gas (GHG) emissions produced from processing food waste for each option. We consider emissions generated by the processing facilities and by transportation required for the off-campus option and for transportation of food waste diverted to regional waste facilities due to contamination for the on-campus option. We also consider background emissions from electricity consumed by the on-campus option. Finally, we include a partial evaluation of CHP power production for the off-campus option but were not able to include a full energy balance evaluation for the off-campus option due to incomplete data.

We focus on the food waste generated on the UBC Point Grey campus that is delivered to compost facilities. We do not consider the fate of campus food waste that is not diverted to composting and remains in the waste stream.

Our study is a UBC Social Ecological Economic Development Studies (SEEDS)[3] project that was undertaken with support from the UBC Campus Sustainability Office.

METHODS

Functional Unit

For our study, we defined our functional unit as mass of food waste, in metric tonnes, since this is the unit of interest for UBC, and is common for the alternative systems under consideration as well as for the waste stream. In consultation with the project sponsor, we selected the mass of food waste expected to be diverted to compost in 2014, which is estimated to be 650 tonnes. Thus, our *functional unit* is defined as: *650 tonnes of UBC food waste*.

System Description

We considered three sub-systems to be within the scope of our study. The two *organics processing systems* themselves (and waste disposal facilities for diverted food waste due to contamination), the *transportation* between UBC and the organics processing facility for the off-campus option and to waste disposal facilities for diverted food waste. We also considered *electricity consumption* at the organics processing systems. Methods for each system are described in further detail below.

[3] SEEDS program description.

We did not consider the fate of UBC food waste that was not diverted to the organics processing systems (i.e., campus food waste that is directly diverted to the waste stream). We also did not consider landscape organic waste (which is processed by UBC in a separate system), or bark mulch (which is processed in the same on-campus system as food waste) since the desire was to compare emissions from the food waste component that is common to both systems.

Food Waste

The food waste systems considered include the on-campus aerobic compost system, the off-campus anaerobic digestion and composting system, and landfill and waste-to-energy (WTE) options for diverted waste. For the mass flow of organic food waste, we assumed that 5% of food waste was non-organic contamination, and that due to contamination 20% of food waste was diverted from organic processing stream to the waste stream[4]. For food waste diverted to the waste stream, we assumed waste was distributed among regional waste facilities based on reported distribution proportions (Table 1).

Table 1. Waste distribution among Metro Vancouver Facilities.[5]

Facility	Fraction (%)
Vancouver Landfill	40
Cache Creek Landfill	38
Burnaby WTE	22

For the off-campus option, it was assumed that food waste would be delivered to the Earth Renu Energy Corp. facility on Annacis Island, where the 5% non-organic contaminants would be removed. The uncontaminated food waste would then be delivered to the Harvest Power BC anaerobic digestion facility in Richmond BC.

Emission Factors

CO2e emission factors for the food waste systems were obtained from multiple sources (Table 2). We used local emission factors where available and were able to obtain BC specific factors for aerobic composting with negative aeration (we considered both the UBC in-vessel system and the Harvest Power composting system to be negative aeration since they use bio-filtration

[4] Information provided by UBC Building Operations
[5] Metro Vancouver presentation.

systems). The compost sequestration factor was based on field studies undertaken by the US Environmental Protection Agency (USEPA 2006).

Landfill emission factors were based on approved methodologies and data specific to BC landfills (CRA 2013; SSG 2013). The emission factor for anaerobic digestion was based on the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas (GHG) inventories (IPCC 2006).

Table 2. Emission Factors for organic waste.

Type	Emission Factor MTCO2e/MT	Source
Compost (Negative Aeration)	0.087	CAR (2013) and GCC (2011)
Compost Carbon Storage	-0.20	USEPA (2006)
Anaerobic Digestion	0.028	IPCC (2006)
Vancouver Landfill	1.54	SSG (2013) and CRA (2009)
Cache Creek Landfill	0.68	SSG (2013) and CRA (2009)
Burnaby WTE	0.08	USEPA (2006)

Transportation

Transportation was only considered for off-campus transport of food waste (to the off-campus facility and to regional waste disposal facilities). On-campus transportation of food waste (from collection bins to the on-campus processing facility) was not considered, since this was expected to be the same for each system considered.

Distances to the off campus sorting and anaerobic digestion facilities and regional waste facilities were determined from Google Maps (Table 3). Based on information provided by the project sponsor, fuel efficiency was assumed to be 40 litre/100km and truck capacity was assumed to be 16 tonnes. We assumed one delivery per week for trips from UBC to the off-campus facility and fractional trips for waste to regional waste facilities. For CNG fueled trucks, we used an external, NRC sponsored, calculator to determine the fuel consumption of the vehicles over the distances of each listed route (Table 3; NRC 2012).

Table 3. Distances and CNG consumption for transportation.

Destination	Distance (km)	CNG Fuel/Trip (m3)	Description
Earth Renu (Annacis Isand)	62	27	sorting Facility (organics from UBC)
Harvest Power (Richmond)	20	9	A.D. facility (organics from Earth Renu)
Vancouver Landfill	53	23	waste from UBC
Cache Creek Landfill	724	314	waste from UBC
Burnaby WTE	48	21	waste from UBC
UBC	50	22	soil delivery from Harvest Power

Emission Factors

We obtained emissions factors for transportation fuels considered in our study that are based on BC government guidelines (Table 4).

Table 4. Emission factors for transportation fuels.

Fuel Type	Emission Factor CO2e	Source
Diesel	2.60 kg/litre	BCMoF (2012)
Compressed Natural Gas	2.16 kg/m3	BCMoF (2012)

Electricity

BC Hydro electricity used to provide power to organics processing facilities is a background emission source in our study. We obtained a BC government emission factor for BC Hydro electrical energy production and an emission factor that accounts for BC Hydro power imports (Table 5).

Table 5. Emission factors for BC Hydro electricity production.

Electricity Source	Emission Factor MTCO2e/GWH	Source
BC Hydro	25	BCMoF (2012)
BC Hydro	84	Dowlatabadi (2011)

Global Warming Potential

We used recently released global warming potential (GWP) values for methane and nitrous oxide (Table 6; IPCC 2013). We adjusted emission factors that were based on 2007 IPCC emission factors (IPCC 2007).

Table 6. Global warming potentials for methane and nitrous oxide.

	GWP		Conversion	
GHG	2013	2007	Factor[1]	Source
CH4	28	25	1.12	IPCC (2013, 2007)
N20	265	298	0.89	IPCC (2013, 2007)

[1]Used to update emission factors that were based on 2007 GWPs.

Combined Heat and Power (CHP)

To estimate the annual energy output of the combined heat and power unit, we first determined the annual methane production volume from the anaerobic digester using the annual mass of organic material digested and the biogas generation rates and methane concentrations obtained from Harvest Power (Table 7). Using a using a high heating value of 39.1 MJ/m3 for natural gas and an overall efficiency of 75%, the total energy output from the CHP unit was estimated using a low volume, low concentration scenario and high volume, high concentration scenario.

Table 7. CH4 Production values from Harvest Power.

	Low Value	High Value
Biogas Generation (m3/tonne)	50	90
CH4 Content of Biogas (% by vol)	65%	75%

RESULTS

The UBC In-Vessel Composting System

We determined mass flows and component emissions for the on-campus system, diagramed below (Figure 1). The mass input to the on-campus system is 650 tonnes per year. Sorting at the facility results in an estimated 20% of the material diverted to disposal due to 5% inorganic contaminants . The rejected matter is transported to regional waste facilities at located in Delta(40%), Cache Creek(38%), and the Burnaby WTE center(22%). All mature compost from organics processing is utilized as soil for UBC landscaping.

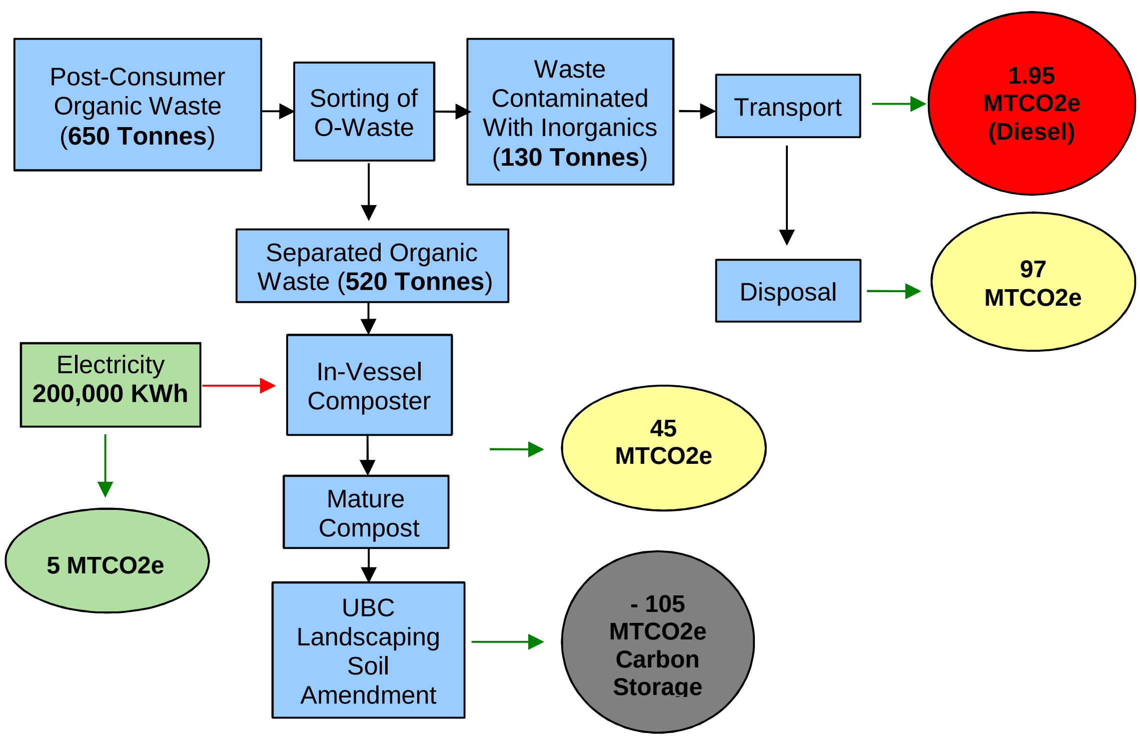

Figure 1. Mass flow and CO2e emissions from UBC In-vessel Compost System. Red represents transportation emissions, green represents background electricity emissions, yellow are composting and disposal emissions and grey represents net carbon stored in soil.

Harvest Power Anaerobic Digestion System:

We determined mass flows and component emissions for the off-campus system, diagrammed below (Figure 2). The mass input to the off-campus system is 650 tonnes per year. Food waste first goes the Earth Renu facility for sorting of inorganic waste (estimated 5%) and uncontaminated organics then goes to Harvest Power for anaerobic digestion. After the AD process, 50% of the organic mass then goes to the turned windrow for composting. The produced mature compost then is transported to UBC to be utilized as landscaping soil.

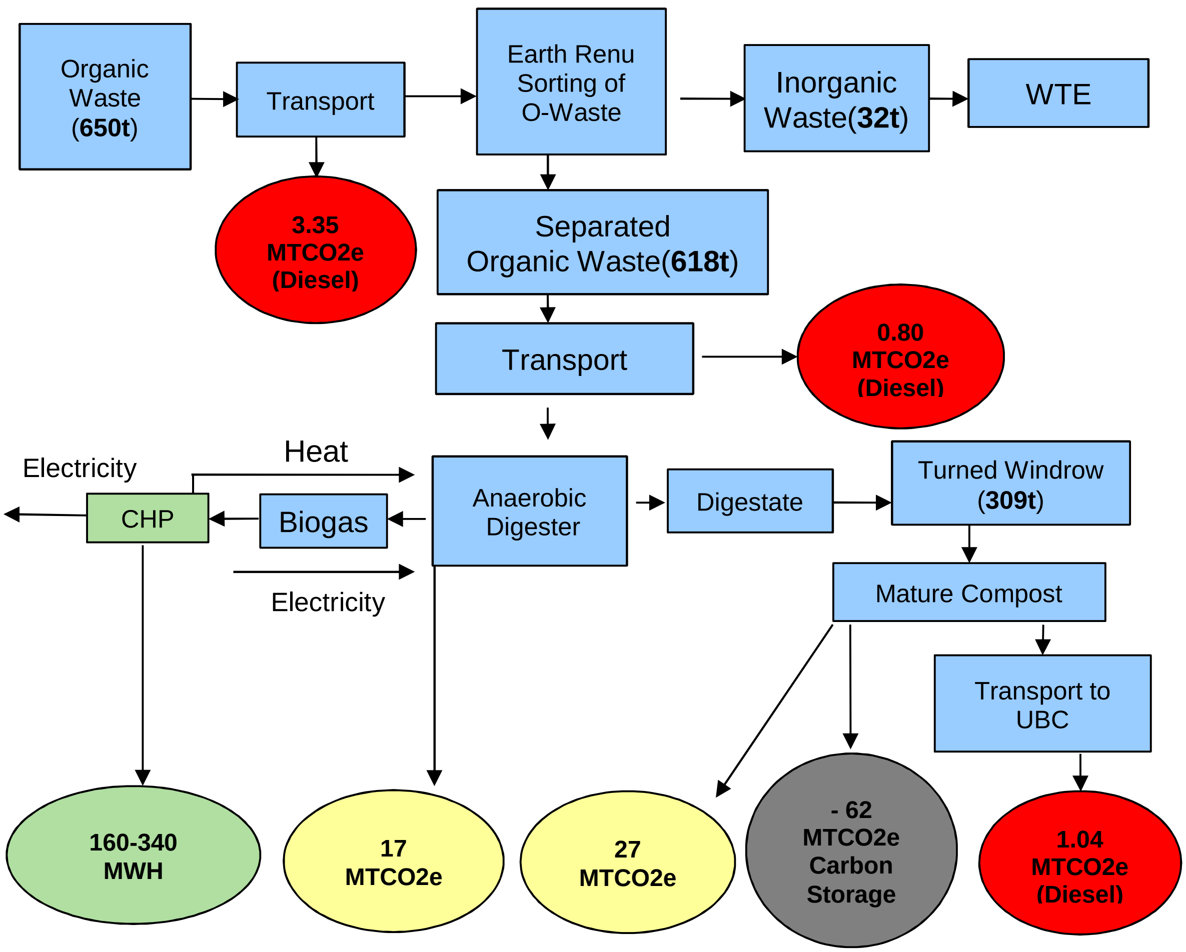

Figure 2. Mass flow and CO2e emissions for off-campus anaerobic digestion system. Red represents transportation emissions, green represents estimated power production, yellow are emissions from anaerobic digestion and composting, and grey represents net carbon stored in soil.

System Emissions for Organic Waste Processing Options

On-Campus Option

We determined the emissions from the composting system using the described on-campus option and mass flows. The largest individual source of emissions was from the disposal of the rejected matter which is responsible for 97 MTCO2e annually (Figure 3; Table 8). These emissions are from the rejected 20% of the total mass, primarily due to the organic mass disposed of in regional landfills.

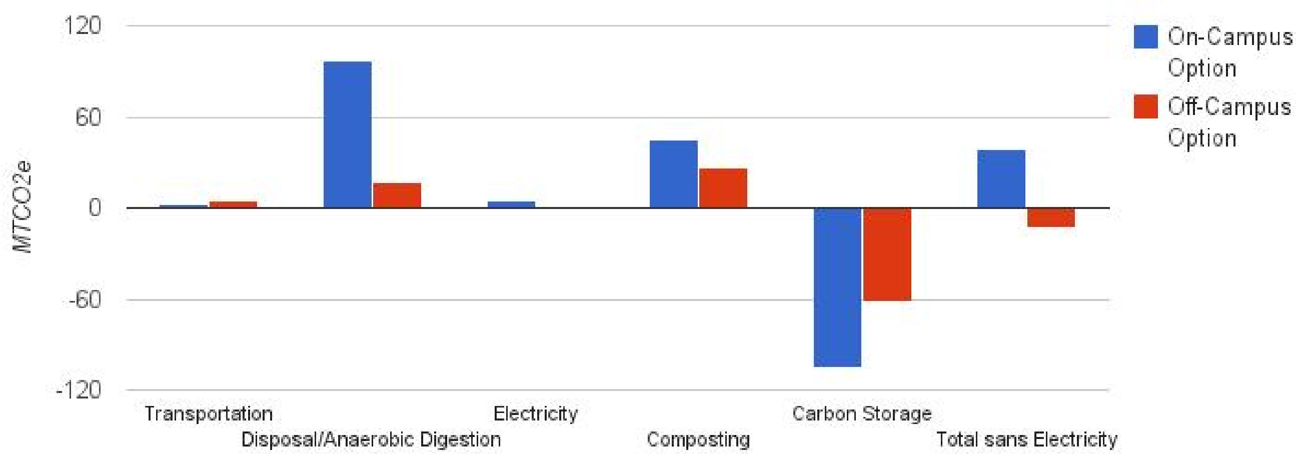

Figure 3. System CO2e emissions for on-campus and off-campus options.

Table 8. System CO2e emissions for on-campus and off-campus options.

Options	Transportation	Disposal/Anaerobic Digestion[1]	Composting	Carbon Storage	Total[2]
On-Campus	1.9	97	45	-104	39
Off-Campus	5.2	17	27	-62	-13

[1]Disposal emissions from on-campus option, AD emissions from off-campus option.
[2]Total does not include 5 MTCO2e electricity emissions for on campus options.

From the established route distances, disposal truck capacities and fuel efficiencies, transportation was found to only produce 1.9 MTCO2e/year on-campus and 5.2 MTCO2e/year for the off-campus option. This figure indicates that the emissions from transportation are the smallest in magnitude of any of the contributing factors addressed in this study.

We found that the contribution from grid-electricity consumption was similarly small in magnitude. Using the BC Hydro stated carbon intensity of its electricity and the stated annual electricity consumption of the In-Vessel Composter, the annual emissions were determined to be 5.0 MTCO2e.

The emissions from the composting of the 80% of the total mass retained on campus was split into two components; the emissions released during composting and the carbon stored in the compost mass. The methane and nitrous oxide emissions from the composting process were found to contribute 45 MTCO2e/year, coming from 520 tonnes of mass disposed. Beyond the process emissions, the composted material was calculated to have sequestered 104 MTCO2e, based on the EPA carbon flux figures.

We found that total annual emissions were 39 MTCO2e for the on-campus option. This figure did not include emissions from electricity for reasons outlined in the on-campus option.

Off-Campus Option

We determined emissions for the off-campus option using the outlined methodology for the system and the distances and emissions factors obtained for this option (Figure 3; Table 8). Since none of the organic material was rejected, there was no waste disposal category in the on-campus option. All of the organic matter delivered to Harvest Power, 95% of the total mass, was assumed to be processed in the anaerobic digester, the emissions from which, were determined to be 17 MTCO2e/year.

For the emissions from transportation, since the trucks were assumed to be the same as the ones used in the on-campus option, the fuel efficiencies and capacities were not changed. From the trip distances and mass transported, the emissions were found to be 5.2 MTCO2e/year.

Since no values for electricity consumption at Harvest Power could be obtained, emissions from electricity could not be calculated. For the sake of consistency, the total annual emissions from the off-campus and on-campus options were calculated excluding the emissions from electricity.

For the mass composted in the turned windrow after being processed in the anaerobic digester, the same composting emission and storage factors were used as in the on-campus option. From the mass composted at Harvest Power, we determined that the annual emissions were 27 MTCO2e and the carbon mass stored in the composted material was 62 MTCO2e.

Sensitivity Analysis

We considered the impact of switching the fuel of the disposal trucks from diesel to compressed natural gas to assess the sensitivity of emissions to transportation fuel. For the on-campus option, switching fuels resulted in a decrease in emissions of 0.19 MTCO2e/year, a 9.9% reduction (Figure 4; Table 9). Similarly, switching fuels for the on-campus option reduced annual emissions by 0.47 MTCO2e or 9.0%.

We also studied the response of emission rates to the carbon intensity of grid electricity for its contribution to the on-campus option's emissions. Using the BCHydro carbon intensity of 25 tonnes/GWH, the annual emissions from the In-Vessel Composter were calculated to be 5.0 MTCO2e. When the alternative carbon intensity for grid electricity of 84 tonnes/GWH was utilized, the annual emissions from consumed electricity were found to be 17 MTCO2e (Figure 4; Table 9).

With 20% of the total mass being diverted for disposal, the total emissions of the on-campus option were 39 MTCO2e/year. When we analyzed the on-campus option with a reduced diversion rate of 5%, the total annual emissions decreased to -71 MTCO2e (Figure 4; Table 9). This difference reflected a reduction of the disposal emissions, a decrease of the transportation emissions, an increase of the compost emissions and an increase of the stored carbon in the compost material associated with composting all of the organic material on campus

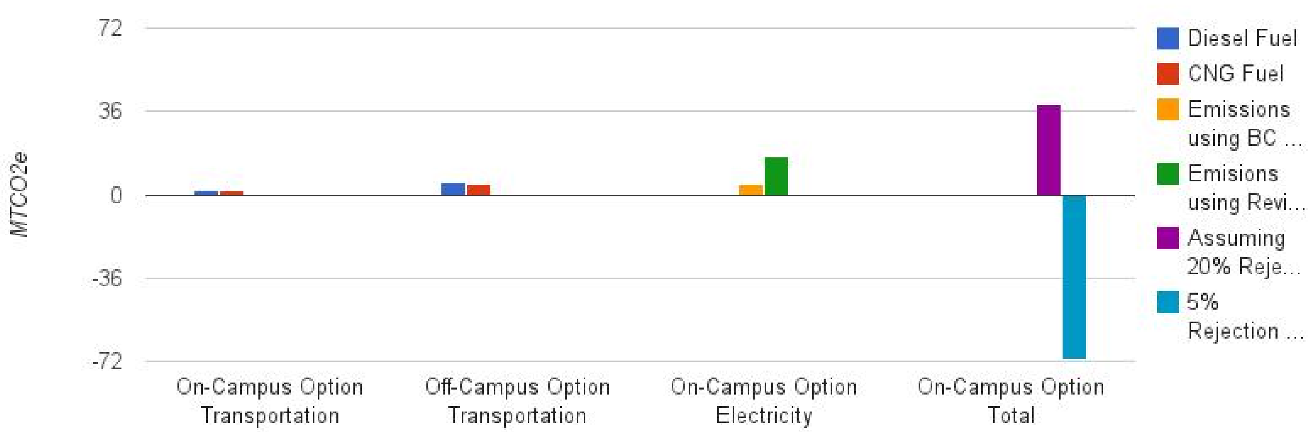

Figure 4. Sensitivity analysis results for transportation, electricity and rejection rate.

Table 9. Sensitivity analysis results for transportation, electricity and rejection rate (MTCO2e).

	Fuel		Electricity Factor		Rejection Rate	
Options	**Diesel**	**CNG**	**BC Gov**	**PICS**	**20%**	**5%**
Transportation (UBC)	1.9	1.8	-	-	-	-
Transportation (HP)	5.2	4.7	-	-	-	-
Electricity (UBC)	-	-	5	17	-	-
Rejection Rate (UBC)	-	-	-	-	39	-71

DISCUSSION

We found that of the two options we considered, the off-campus anaerobic digestion option had lower GHG emissions based on the emission factors and assumptions we used: from an annual input of 650 tonnes of food waste, the off-campus option generated - 13 tonnes of CO_2e emissions compared to 39 tonnes CO_2e emitted for the on campus option, a net difference of 52 tonnes CO_2e.

We determined that the highest emission source in the system we evaluated was from rejected waste sent to regional waste facilities from the on-campus option (97 tonnes CO_2e). This was due to emissions from the Vancouver and Cache Creek landfills (WTE had a relatively small emission factor compared to landfill emission factors). The single most impactful factor was carbon stored in soils generated from compost (- 104 tonnes CO_2e for the on-campus option). Finally, we found that transportation related emissions made up a relatively small proportion of our results.

From our sensitivity analysis, we learned that reducing rejected food waste due to contamination for the on-campus option has a significant impact on emissions (resulting in a change from 39 tonnes emitted to -71 tonnes stored, a net difference of 110 tonnes CO_2e). We also found that considering an alternative emission factor for background electricity emissions, that considered emissions from BC power imports, had a relatively small impact on emissions (we note that emissions from background electricity were reported on but not included in totals because we were unable to determine energy consumption emissions for the off-campus options). Finally we determined that considering an alternative fuel source for transportation (compressed natural gas) had negligible impacts on our results.

Limitations and Future Work

Future work should focus on completing the full energy balance for the off-campus option, which was were not evaluated in our study. Electricity and heat generated from the CHP system at Harvest Power would offset emissions from grid electricity and fossil fuel based natural gas, and need to be considered to determine the net emissions related to energy consumption and production.

Additional work to complete the mass balance for the off-campus option should also be pursued. We estimated mass flow from the AD to composting system based on an estimate from the literature and we did not consider emissions (or emission offsets) associated with other outputs from the AD system such as liquid fertilizers or liquid wastes not recycled or sent to the compost system.

In our review of literature we noted that some recent estimates for CO2e emissions from AD systems were an order of two or three times higher than the IPCC (2006) factor we used in this study (Phong 2012; DHV 2010). Since we could not relate the cited factors to the type of AD system employed by Harvest Power, we did not use them in our study. These results, however, suggest that GHG emission factors for AD warrant further consideration and review in future studies.

Finally, while we limited our scope to one environmental impact type, and did not evaluate the full system, we note that our evaluation could be expanded to consider a full life cycle analysis (LCA), that includes the fate of campus food waste not diverted to processing facilities should be considered, along with a full range of environmental impacts, including human health, local smog impacts and local ecosystem impacts.

Conclusions

Based on our preliminary findings, we conclude that both the on-campus and off-campus options would provide significant emission reductions compared to emissions from food waste delivered to a regional waste facility. We recommend that UBC further evaluate the energy balance, mass flows and end products for the Harvest Power option, and consider a full range of environmental impacts for both systems. Finally, we recommend that UBC consider the benefits of including a waste sorting system to reduce or eliminate rejected food waste in any future processing options implemented by UBC.

APPENDIX 1: EQUATIONS

On-Campus Option

Disposal

$$m_{site} = m_{total}*(r_{rejection} - r_{inorganic})*r_{site} \quad (1)$$

$$C_{disposal} = m_{site}*c_{site} \quad (2)$$

Disposal Transportation

$$C_{transport} = d_{site}*f_{diesel}*c_{diesel}*m_{site}/m_{capacity} \quad (3)$$

Electricity

$$C_{electricity} = E_{electricty}*c_{electricity} \quad (4)$$

Composting (emissions)

$$m_{compost} = m_{total}*(1-r_{rejection}) \quad (5)$$

$$C_{compost} = m_{compost}*(c_{comp,CH4} + c_{comp,N2O}) \quad (6)$$

Composting (storage)

$$S_{compost} = m_{compost}*s_{compost} \quad (7)$$

Off-Campus Option

Transportation

$$m_{organic} = m_{total}*(1-r_{inorganic}) \quad (8)$$

(To Earth Renu)

$$C_{trans,ER} = t_{ER}*d_{ER}*f_{diesel}*c_{diesel} \quad (9)$$

(To Harvest Power)

$$C_{trans,HP} = d_{HP}*f_{diesel}*c_{diesel}*m_{organic}/m_{capacity} \quad (10)$$

(To UBC)

$$C_{trans,UBC} = d_{UBC}*f_{diesel}*c_{diesel}*roundup(r_{AD,compost}*m_{organic}/m_{capacity}) \quad (11)$$

Anaerobic Digestion

$$C_{AD} = m_{organic}*c_{AD} \quad (12)$$

Composting (emissions)

$$m_{AD,compost} = m_{organic}*r_{AD,compost} \quad (13)$$

$$C_{AD,compost} = m_{AD,compost}*(c_{comp,CH4} + c_{comp,N2O}) \quad (14)$$

Composting (storage)

$$S_{AD,coompost} = m_{AD,compost}*s_{compost} \quad (15)$$

Annual CH4 Generation in Anaerobic Digester

$$V_{CH4} = m_{organic}*v_{biogas}*r_{CH4} \quad (16)$$

Annual Energy Output from CHP unit

$$E_{CHP} = V_{CH4}*HHV_{CH4}*\eta_{CHP} \quad (17)$$

Sensitivities

Transportation (CNG)

For all transportation equations, substitute ($F_{CNG}*c_{CNG}$) for ($d_{site}*f_{diesel}*c_{diesel}$) (18)

Definition of Terms

C_{AD} = emissions from anaerobic digestion (MTCO2e/year)

c_{AD} = emission factor for anaerobic digestion (MTCO2e/tonne)

$C_{AD,compost}$ = emissions from composting in off-campus option (MTCO2e/year)

c_{CNG} = emission factor for compressed natural gas (MTCO2e/m^3)

$C_{compost}$ = emissions from composting in on-campus option (MTCO2e/year)

$c_{comp,CH4}$ = emission factor for CH4 emissions from composting (MTCO2e/tonne)

$c_{comp,N2O}$ = emission factor for N2O emissions from composting (MTCO2e/tonne)

c_{diesel} = emissions factor for diesel fuel (MTCO2e/L)

$C_{disposal}$ = emissions from specific waste disposal site (MTCO2e/year)

$C_{electricity}$ = emissions from grid electricity consumption (MTCO2e/year)

$c_{electricity}$ = carbon intensity of grid electricity (MTCO2e/GWH)

c_{site} = emissions factor for organic matter at specific waste disposal site (MTCO2e/tonne)

$C_{transport}$ = emissions from transportation to specific waste disposal site (MTCO2e/year)

$C_{trans,ER}$ = emissions from transportation from UBC to Earth Renu (MTCO2e/year)

$C_{trans,HP}$ = emissions from transportation from Earth Renu to Harvest Power (MTCO2e/year)

$C_{trans,UBC}$ = emissions from transportation from Harvest Power to UBC (MTCO2e/year)

d_{ER} = round-trip distance from UBC to Earth Renu (km)

d_{HP} = round-trip distance from Earth Renu to Harvest Power (km)

d_{UBC} = round-trip distance from Harvest Power to UBC (km)

d_{site} = round-trip distance from UBC to specific waste disposal site (km)

E_{CHP} = total thermal and electrical energy produced by combined heat and power generator (MJ/year)

$E_{electricty}$ = electrical energy consumption (GWH/year)

F_{CNG} = compressed natural gas consumed on a single round-trip route of a specific distance (m^3)

f_{diesel} = fuel consumption rate of diesel vehicle (L/100km)

HHV_{CH4} = high heating value of methane (MJ/m^3)

$m_{AD,compost}$ = organic mass composted in off-campus option (tonne/year)

$m_{capacity}$ = mass capacity of disposal vehicles (tonne)

$m_{compost}$ = organic mass composted in on-campus option (tonne/year)

$m_{organic}$ = organic mass in waste stream (tonne/year)

m_{site} = organic mass disposed of at specific waste disposal site (tonne/year)

m_{total} = total mass of waste stream (tonne/year)

η_{CHP} = overall efficiency of combined heat and power generator based on HHV (%)

$r_{AD,compost}$ = rate of organic mass composted in off-campus option (%)

r_{CH4} = methane content of biogas by volume (%)

$r_{inorganic}$ = rate of inorganic mass in waste stream (%)

roundup( ) = round value in parenthesis up to nearest integer

$r_{rejection}$ = rejection rate of waste stream (%)

r_{site} = rate of total rejected waste diverted to specific waste disposal site (%)

$S_{AD,coompost}$ = carbon stored in compost in off-campus option (MTCO2e/year)

$S_{compost}$ = carbon stored in compost in on-campus option (MTCO2e/year)

$s_{compost}$ = carbon storage factor for composted material (MTCO2e/tonne)

t_{ER} = number of vehicle trips to Earth Renu from UBC (1/year)

v_{biogas} = biogas production from anaerobic digestion of organic mass (m^3/tonne)

V_{CH4} = volume of methane produced from anaerobic digestion (m^3/year)

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