Omni-Processor: Waste-to-energy technology assessment – Final presentation –

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Executive Summary

- To be viable for the urban developing world, sludge treatment technologies face strong constraints in terms of cost, complexity, and space. Consequently, there has been extremely limited commercial development of technologies appropriate for this setting.
- There is no single process that represents a complete solution for fecal sludge treatment. A solution feasible today would entail anaerobic digestion coupled to thermo-mechanical treatment. Gasification has a higher technical merit than thermo-mechanical technologies, and should be explored in the medium term as a post-digestion secondary treatment of sludge.
- Anaerobic digestion almost certainly needs to be part of the Omni-Processor solution. It has a low CapEx, small footprint, is net energy positive, mature, and highly amenable to co-processing with food or other organic waste. Above all, it is a simple and robust process that can be almost completely passive, with no mechanical parts. Two academic groups in Brazil stand out as leaders in the implementation of low-cost digester technology.
- Because anaerobic digestion is not a complete treatment, it needs to be coupled with other secondary treatments. Pathogens can be inactivated by biogas-powered thermal treatment of the sludge at a modest 70°C, or in a thermo-mechanical pelletizer. Trickling filters can treat the water output (supernatant).
- Thermo-mechanical processors can be simple but energy intensive solutions to sludge disposal after primary digestion. Consider this technology when avoided sludge tipping fees can offset its energy costs, or if it can be powered by digester biogas.
- No gasification or pyrolysis technology is mature for sludge treatment. Most are unfeasible due to their high expense and sophistication, typically operating at much larger scales and budgets.
- Downdraft gasifiers, such as being developed by Husk Power, are one exception. They are relatively simple, and are being proven out in rural electrification schemes in India. Dried, pelletized sludge could be co-processed with other agricultural waste to generate energy, but further development of the technology is required. Pyrolysis, while not unfeasible, is unproven and therefore technically risky as a sludge treatment technology.

Agenda

- Overview and Methodology
- Review of processes
  - Comparative analysis
  - Anaerobic digestion
  - Gasification
  - Pyrolysis
  - Thermo-mechanical treatment
- Technology deep dives
  - Fixed-bed gasifier
  - Fast pyrolysis
  - Upflow anaerobic sludge blanket
- Quantitative analysis
  - Ranking candidate technologies
- Interview insights
- Recommendations

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Our understanding of the Bill and Melinda Gates Foundation's needs

- **To catalyze innovation in the effective collection, storage, treatment, and conversion of waste, the** Bill and Melinda Gates Foundation (BMGF) **is seeking to develop an "Omni-Processor"**, a device capable of treating and converting human fecal waste streams into useful outputs.
- Ideally, the Omni-Processor will:
  - accept a range of waste feedstocks and co-process these inputs into a locally valuable resource such as heat, fuel, compost, or water
  - have a small-footprint, stand-alone device processing fewer than five tons of waste per day to serve 1,000 – 5,000 people in an urban developing-world setting
  - Cost less than $10/person/year, when accounting for net costs and benefits
  - Run as a stand-alone unit, independent of grid, water, or sewer systems
- The BMGF believes the most promising processes **are thermo-mechanical treatment, pyrolysis, incineration* and gasification**, although there may be other processes that are viable, such as anaerobic digestion or microbial fuel cells
- In order to guide its technology development roadmap for the Omni-Processor, the BMGF needs a deeper understanding of these processes and how they could be used or modified for the treatment of human fecal sludge
- The BMGF would like to know the candidate firms, universities, technologies, or products/systems to pursue for the next steps. It would like the final product to be a description of the key players and technologies for each of the four processes.

*after our preliminary research ruled out the viability of incineration, we substituted anaerobic digestion as a process of primary interest for the project

Methodology – The need for a low-cost, simple, small footprint device was the over-arching goal of our research

- Our approach was dictated by the BMGF's goal to develop a small footprint device (a few metres square base) that serves 1,000 – 5,000 people in a developing world urban setting. Constraints include simple operation and maintenance, low cost, and few external inputs (electricity, water, chemicals).
- Each aspect of this goal is important:
  - **Low cost** – cost is rarely a constraint imposed on innovation, and simplicity may be rarer still; there is a plethora of technologies under development for sludge treatment, but most can be classified as "high CapEx" approaches which bring high technical risk. Examples include thermal hydrolysis, microbial fuel cells, and various advanced gasification and pyrolysis methods
  - **Small footprint** – the lowest cost option is undoubtedly a natural treatment system such as a waste stabilization pond or constructed wetland, but these are ruled out both for size and the urban setting
  - **Simple operation and maintenance –** we assume that if something can break, it will, and local capacity and technical skills must be sufficient to keep units operational. Simplicity is paramount to robust operation in a developing world urban setting.
- The processes we investigated are as follows:
  - Anaerobic digestion, gasification, pyrolysis, and thermo-mechanical treatment
  - Each of these processes represents a distinct approach to sludge treatment
  - For each *process*, there are a variety of *technologies* - i.e. different versions, or flavors
- We identified the leading technologies viable in this setting and analyzed them in a comparative, quantitative framework
- Few companies are targeting sludge treatment in the developing world. Indeed, the vast majority of technology companies are developing solutions for large-scale, rich-world implementation. We highlight these players as appropriate, but focused our research and interviews on academic institutions.

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Comparative analysis: The processes differ across a wide range of metrics…

Process	Pre-treatment	Post-treatment	Stage	Cost	Operating temperature	Residence time	Emissions	Useful outputs
Anaerobic digestion	None needed; agitation or chemicals can improve process	De-watering, drying, incineration or heat treatment	Small/med/ large scale, deployment gobally	Low to medium	20 C – 35C (mesophilic) 55C (thermophilic)	6h to 30 days	Biogas potent GHG if not captured or flared	Biogas can be used for post-treatment or burned for energy
Mechanical + thermal treatment	None needed	Dewatering, water treatment	Mature for other feedstocks (e.g. MSW)	Medium	100C – 300C	0.5h – 1h	Biogas	Fertilizer possible
Incineration	Dewatering, drying	Ash disposal	Large scale, global	High	850C – 1100C	< 10 s	High; requires costly scrub	Building products
Gasification	Dewatering, drying	None	Early stage development at small scale	High	600 C – 1100 C	10 s – 1h	Potentially high	Pellets; syngas for heat/ electricity
Pyrolysis	Dewatering, drying	None	Early stage development at small scale	High	350 C– 750 C	10 s – 1h	Moderate	Bio-diesel, bio-char

…each having pluses and minuses

Process	Advantages	Disadvantages	Developing world applicability	Co-processing potential
Anaerobic digestion (AD)	- produces methane for net energy production - rapid treatment - small footprint - low to medium cost	-does not remove pathogen load - can require long retention times - bacteria can be inhibited - large volumes output	Relative simplicity, cost, suitability to wet feedstock, and scale show promise as partial solution.	Can be effective complement to other organic waste (MSW) digestion. Needs coupling with add'l post treatment
Gasification	- outputs useful syngas -"complete" treatment - relatively clean emissions compared to incineration	- requires high degree of dewatering - typically high CapEx - complex process - may require emissions treatment	Complete treatment and small footprint are positives, but cost and complexity pose great challenges. Needs "Husk Power" type approach to be successful.	Down-draft gasifiers require a certain feedstock density, but viable for co-processing. Other techs can be sensitive to feedstock chemistry and morphology.
Pyrolysis	- produces useful bio-oil - complete treatment - lower T than gasification - less emission concern	- requires dry feedstock - costly and complex - bio-oil may be poor quality		
Thermo-mechanical treatment	- Low-tech - Likely inactivates most pathogens	- requires external energy - no energy generation - disposal challenge	Attractive in its simplicity, but needs substantial energy inputs. Likely a partial solution.	Well-suited to co-processing; can be coupled with AD
Incineration	- Large volume reduction - complete pathogen inactivation	-prohibitive capital costs - emissions can be harmful -requires net input of energy to dry sludge	Large scale, high cost, and potential for toxic emissions; inappropriate for developing world	Can be combined with other hazardous waste incineration.

Sludge moisture content determines the most suitable process

Sludge characteristics

Adapted from Sandec, *Faecal Sludge Treatment (2002)*

	Raw fecal matter (e.g. from UDT*)	Bucket latrine	Septic tank	Tropical sewage
Description	Feces	Feces and urine (with some cleansing water)	Could be months to years of storage; low concentration	Typical municipal wastewater
Moisture content	75% - 80%	90% - 95%	97%	> 99%

High solids → Low solids

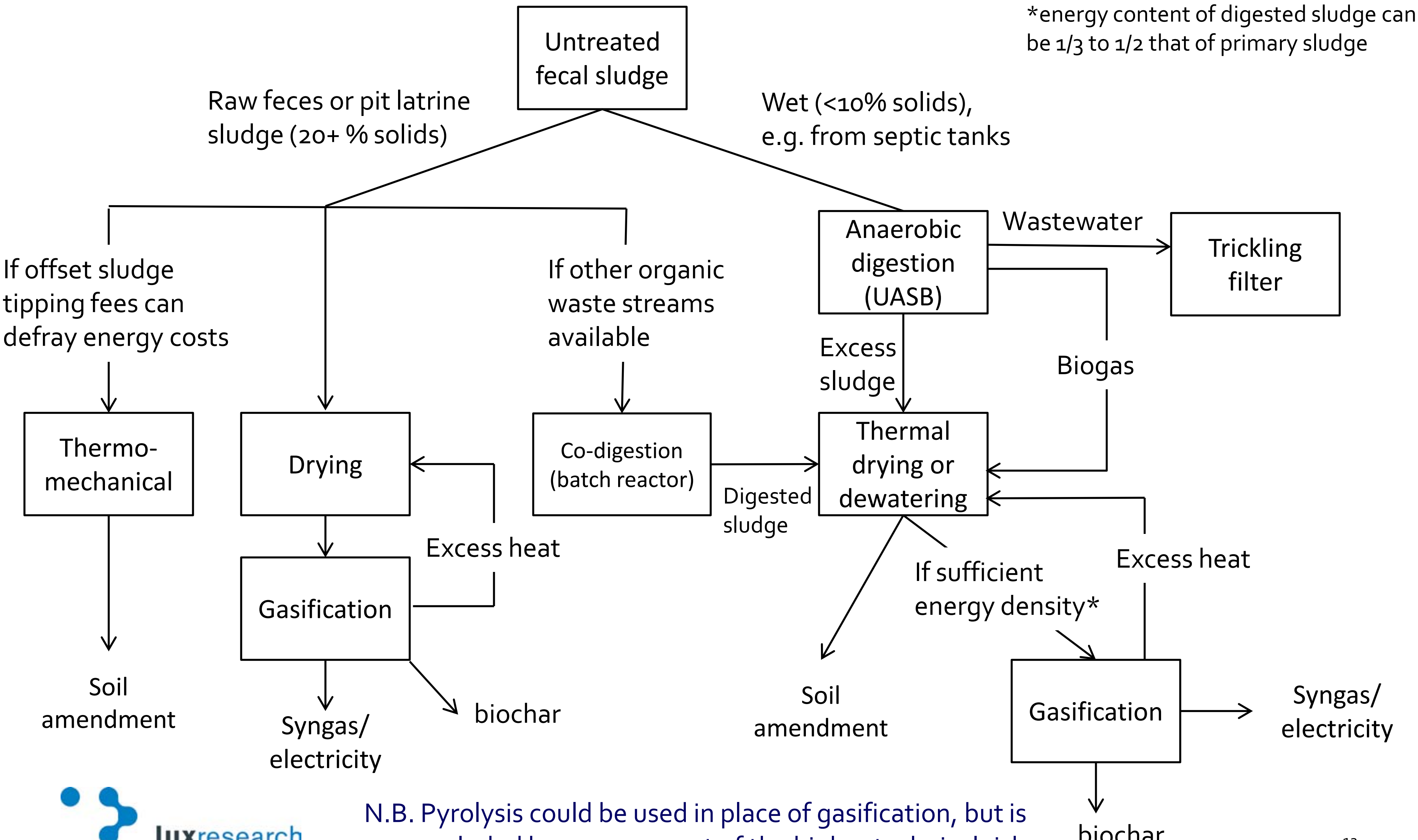
Treatment processes and moisture content

	Pyrolysis	Gasification	Thermo-mechanical	Anaerobic digestion
Preferred moisture content	< 10%	< 10%	< 10%	95% - 98% (low solids) 70% - 80% (high solids)

- Bucket latrine and septic tank sludge are well-suited to a low-solids anaerobic digestion treatment, such as an upflow anaerobic sludge blanket (UASB) digester. Raw fecal matter or latrine sludge could be co-digested with organic waste in a batch digester, or dried and treated thermally.

*UDT – urine diversion toilet

Decision tree: The type of sludge determines the processing options



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N.B. Pyrolysis could be used in place of gasification, but is excluded here on account of the higher technical risk

Anaerobic digestion

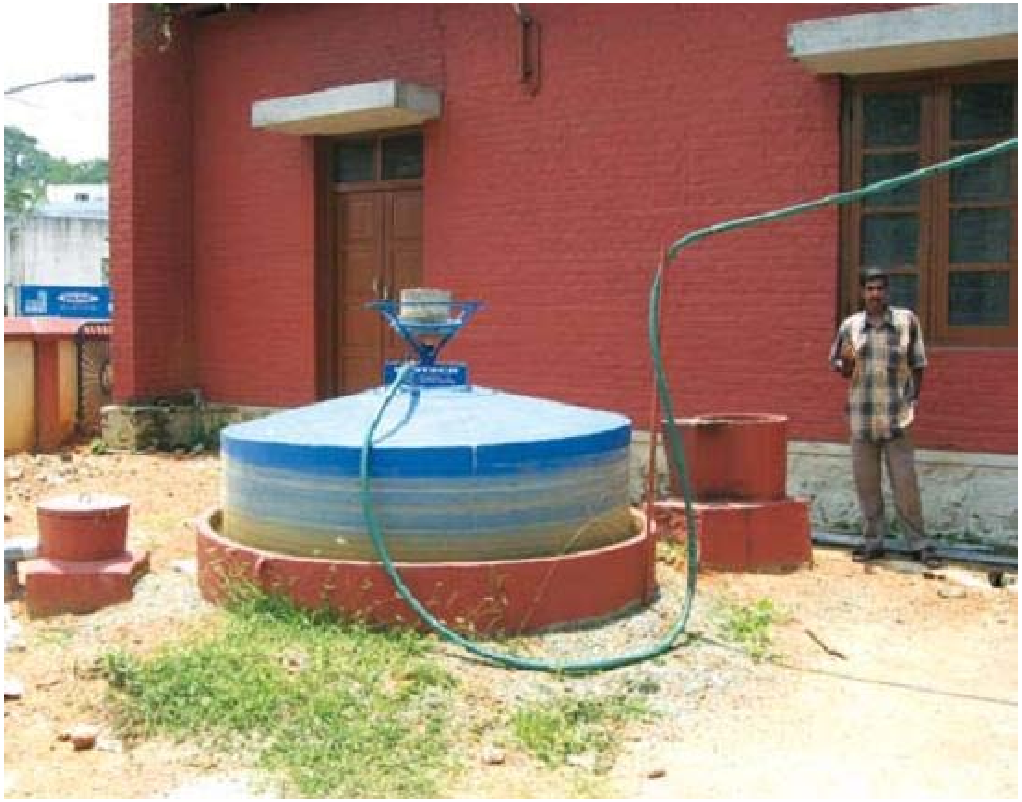


Image: http://bio-gas-plant.blogspot.com/2011/05/biogas-for-sustainable-future.html

Anaerobic digestion is not a panacea, but is well-suited to the developing world

- **Lux Research take –** Anaerobic digestion is the most viable primary sludge treatment technology, with the benefits of low cost, simplicity, small scale, small footprint, and energy generation. Harvest the biogas to thermally inactivate pathogens and help dry sludge for secondary processing.
- **What you need to know**
  - Anaerobic digestion (AD) is compelling primarily because it is low cost and low complexity. Simple reactor designs are almost completely passive, having no moving parts and being driven by fluid flow. They can be scaled down to serve as few as 500 inhabitants, and generate biogas which can be harnessed for several applications, from cooking fuel to sludge hygienization
  - The down-sides are two-fold: it is not a complete treatment (for either wastewater or sludge), and it does not dry the sludge, leaving the issue of what to do with residual the sludge volume problem. These challenges are manageable, and imply that AD will be one part of a greater solution
  - Several Brazilian research groups, such as those at the Federal University of Rio de Janeiro and Minas Gervais, are world leaders in implementing the AD technology in low-cost developing world settings, and we recommend the BMGF engage with these groups (see p. 12)
- **Process description**
  - AD takes place in 3 steps: enzymatic hydrolysis of organics, acidification (converts to hydrogen, formate, acetate, and fatty acids), and methanogenesis i.e. biogas production (H + formate + acetate $\rightarrow$ CH_4 + CO_2)
  - It can take place in one reactor, or in a more costly, complex two step reactor which separates the methanogenesis step
  - Mainly large- and mid-sized installations globally, but there is **growing interest in small-sized plants**
  - Typical sludge retention time is 20 days in "mesophilic" reactors at 25 – 40 C; but can be as short as 6h

Upsides of AD include energy generation and co-processing; the primary down-side is that it is not a complete treatment

- Approx 20% - 30% of organic matter is digested; pretreatment can increase this substantially
- Thermophilic digestion at 50+ C can increase output of biogas and also help inactivate sludge pathogens

Advantages

- Accepts high water content sludge, and therefore does not require energy-intensive dewatering
- Viable for co-processing with organic municipal solid waste (MSW) or food residues
- small footprint (0.03 – 0.10 m^2/person) and low-cost ($12 - $20 p.p. CapEx, $1.0 - $1.5/person/yr OpEx) [Nelson, 2008]
- generates useful biogas (methane) which can be used for cooking, energy generation, or further heat treatment of the sludge [see Borges et al, 2005; Borges et al, 2008]

Challenges

- Does not fully inactivate pathogens (e.g. fecal coliform removal is only 90-99%, helminth eggs remain)
- Further secondary treatment required to treat supernatant (liquid outflow); may include trickling filters, composting, stabilization ponds, or thermal treatment
- Disposal of treated sludge remains an issue – cheapest solution is a drying bed, but thermal drying may be necessary (energy intensive)
- Anaerobic bacteria can be inhibited by many sludge compounds, including ammonia
- Need a seed inoculation of bacteria for start-up, which can be a slow process (up to 3 months to establish viable bacterial population).
- If the microbial colony is lost – e.g. due to a toxic shock – the reactor will be down until it can be repopulated. This suggests designing a system consisting of more smaller size units to build in redundancy and fault-tolerance.

Anaerobic digestion is well-suited to co-processing, and the treated sludge could be dried for gasification or dispersion

- Requires some process control (pH and temperature); this challenge increases in more complex designs, such as thermophilic or two-stage reactors
- If reactor input contains industrial effluent (unlikely in developing world urban slum), sludge will contain residual toxic contaminants like heavy metals

Pre-treatment

- Variety of pre-treatment methods can increase biogas production, including hydrothermal heating, microwave, ultrasonic, ozone, enzymes, NaOH, pulse techniques, wet oxidation, supercritical oxidation
- Most are unfeasibly complex, but some chemical pre-treatments such as increasing the pH to activate ammonia could be viable [see Nelson interview notes, Appendix]

Co-processing potential

- Adding organic MSW, animal waste, or food residues is very viable and may improve process performance in terms of stability and C:N ratio. See, e.g., the Bromma Biogas facility in Stockholm

Coupling to other technologies:

- Aerobic post-treatment via trickling filter/aerated biofilter/ + secondary clarifier which then recycles sludge back to the UASB; this achieves 90+% BOD removal, vs. 55% - 75% for UASB alone
- Biogas can be used to partially dry the sludge for further treatment via gasification or pelletization

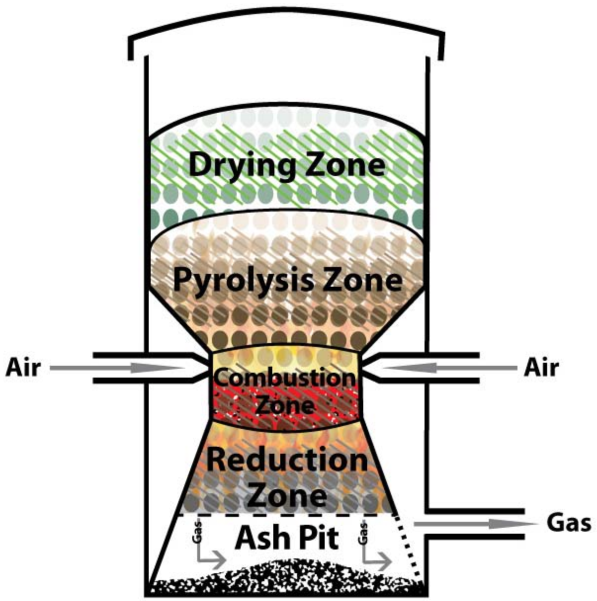
Digestion is most feasible for wet sludges

- **Technologies**
  - Upflow anaerobic sludge blanket – simplest approach and the focus of our analysis
  - Hybrid anaerobic filter, continuous stirred tank reactor (CSTR), fluidized bed, expanded granular sludge bed, plug flow, and several others…
- **Energy requirements**
  - Little to no external energy inputs required for digestion process, unless in thermophilic operation (55+C)
  - Net energy generator in the form of biogas (methane)
- **Water content**
  - The acceptable moisture ratio depends on the type of digester. UASB are fluid pressure-driven devices that typically operate at ~3% - 4% total solids ratio (96% - 97% moisture), which is suited for septic tank waste but not for latrine sludge or raw fecal matter
  - Batch or plug-flow digesters are common for processing organic waste or animal manure, and can operate at high solids ratio (30+%) [Bujoczek et al., 2002]. See examples in India.
  - Co-processing high-solids sludge with a wet organic feedstock (such as food waste) could allow optimization of the water ratio to match the needs of a particular digester process.
- **Volume**
  - Typical retention time for mesophilic reactors is ~20 days [Rulkens, 2008], yielding a process volume of 10 – 100 tons for ao.5 – 5 ton/day facility. Note that this translates to a digester reactor volume of 10 m^3 – 100 m^3, which is well-suited for a small footprint, decentralized approach.

We recommend engagement with leading academic groups in Brazil; most commercial systems are too complex and costly

- **Leading academic groups** for AD implementations in the developing world include:
  - Prof. Carlos Chernicharo – Federal University of Minas Gerais, Brazil – UASB expert
  - Prof. Marcos Von Sperling – author of "Biological Wastewater Treatment in Warm Climate Regions", a veritable bible in the field; very responsive to our inquiries for this project
  - Prof. Perry McCarty of Stanford University, a leading authority on energy generation from wastewater (albeit for the developed world)
- One company explicitly targeting low-income countries is Clearford Industries
  - Small-pipe distributed AD sewage systems with biogas production for deployment in the developing world
  - The technology consists of 4" HDPE pipe leading from homes or businesses using traditional toilets or pour-flush toilets. Traditional septic systems would be bypassed. Pipes from several units lead to distributed anaerobic digesters of 4000-7000 gallon capacity, where fecal matter collects and digests anaerobically as incoming material stirs the system. The system is being rolled out in Peru, Chile, China, and Angola.
  - Lux Research recommends the BMGF engage Clearford as a potential partner.
- There are many companies specializing in anaerobic digestion, but most target large centralized facilities and are therefore unlikely to be viable partners:
  - Harvest Power – AD and gasification of food and ag residues to generate biochar, energy, and fuels
  - **Cambi** – leading developer; complex systems involve thermal hydrolysis pre-treatment
  - **AAT (Austria)** – pre-treatment and anaerobic digestion of sewage sludge and other organic waste
  - **Onsite Power Systems (California)** – offers prefabricated, modular high-solids digesters
  - **Bioprocess Control – o**ptimization of biogas production from anaerobic digesters through sensor and control systems to monitor pH and biogas composition

Gasification



Schematic of a simple gasifier

Husk Power's rice husk gasifier

Image: http://engin1000.pbworks.com/w/page/18942701/Gasifier%20Go-Kart

Image: http://www.huskpowersystems.com/

Most gasification technologies are far too complex and costly; one exception is the simple ag-waste gasifier

- **Lux Research take –** the vast majority of research groups and companies are developing technologies that are complex and costly, requiring large-scale plants to be economically feasible. Select opportunities may exist in the developing world – namely Husk Power's downdraft gasifier in India – but the BMGF should be wary of the technical and economic challenges.
- **What you need to know**
  - Gasification is an attractive technology from many perspectives. It solves both pathogen and sludge volume issues. Many feedstocks can be co-processed. It can be net energy positive, and the generated syngas can be burned to generate electricity or power a motor. Both rich and emerging countries alike suffer from sludge disposal problems, and so many start-up companies are trying to capture a share of the billion-dollar opportunity. However, only one – Husk Power – is gaining traction in a developing world setting. The challenges to gasify sludge are substantial. The feedstock must be dry; the thermal energy required for drying can offset much of the energy produced. Even the simplest gasifiers require some skilled maintenance. Also note that the sludge still requires some form of primary treatment, such as AD.
- **Process description**
  - Dry pelletized fuel enters the reaction chamber (essentially a furnace), where it is heated in a reduced-oxygen environment. The fuel pyrolyzes and then reacts with oxygen to form syngas (mixture of H, CO, CO_2). Gasification technology has been under development for almost 200 years, and was commonly used to power vehicles in the 1940s with wood waste.
  - Many variations exist, including updraft, downdraft, bubbling fluidized bed, rotary kiln, plasma, etc.
  - Process depends greatly on fuel type, and its chemical and physical properties and morphology.
    - Parameters include energy content, moisture content, volatile matter, reactivity, ash content and composition, size distribution, and density
    - For the simplest down-draft version, moisture and density are the two critical variables

Most gasification technologies are far too complex and costly; one exception is the simple ag-waste gasifier

- **Advantages**
  - Can be net energy positive: generates valuable syngas (CO, CO_2, H_2) which can be burned to power a generator or stored for later use.
  - "Complete" sludge treatment inactivates all pathogens
  - Solves sludge disposal problem, since sludge volume is reduce 90+%
  - Relatively clean emissions, though scrubbing equipment necessary
- **Challenges**
  - Usually requires high degree of drying: <10% moisture fraction. Dryers can represent 25% - 50% the costs of a gasifier, and may negate the positive energy balance
  - Typically costly and complex process for sludge treatment, requiring skilled operation and maintenance
  - Feedstock chemistry and morphology (e.g. size, shape) are important variables
  - Reactor start-up requires external energy source (Husk Power uses a battery pack)
- **Pretreatment**
  - Requires dry (<10%), pelletized organic feedstock
  - The simplest gasifier technology, the downdraft gasifier, requires feedstock with a density >270 kg/m^3
- **Co-processing potential:**
  - Most dry organic feedstocks can be co-processed, so if there is a ready source of dry agricultural waste, the economics may be more favorable to combine with sludge treatment
- **Coupling potential**
  - Could be interesting when operated on the back end of an anaerobic digester and a biogas-powered thermal drying system

Most gasification technologies are far too complex and costly; one exception is simple ag-waste gasifiers

- **Technologies**
  - Updraft fixed-bed – the oldest and simplest technology; air enters the bottom and gas exits the top; feedstock enters the top and is heated by convection and radiation from the bottom "hearth zone". Ashes are removed from the bottom.
  - Downdraft fixed-bed – fuel and gas move in the same direction, exiting the bottom of the reactor, which breaks down tars and acids via a hot charcoal bed
  - Fluidized bed – Gas/steam is blown through a solid bed or particles kept in suspension, such as sand or alumina, yielding higher efficiencies than fixed bed but also increasing the complexity. Systems are typically much larger scale than fixed-bed. Three main varieties are bubbling, recirculating, and entrained flow
  - Plasma – involves the generation of a plasma (ionized gas) via the discharge of electricity between two electrodes. Converts organic material to syngas very efficiently, without emission of tar. Produces only an inert glassy slag.
- **Water content**
  - Feedstock must typically be very dry, < 10% moisture content. Water does not add to energy content of generated syngas, and consumes considerable process energy to vaporize. At high temperatures, water dissociates into H and O (H is a component of syngas), but then recombines into water vapor upon cooling, contaminating the syngas. Fixed-bed reactors, which are simpler and cheaper, have a stricter water vapor demand (< 10%) than the more complex fluidized bed designs (< ~30%). Genifuel's process accepts wet feedstock (see p. 23), but is complex and costly.
- **Volume**
  - Most gasifiers are large scale (50+ tons/day) for economic viability, but there are no major technical limitations at small scale. Facilities are typically smaller scale than incinerators. Feedstock requirements are generally 2 tons/day – 50 tons/day.

Gasification companies abound for large-scale waste-to-energy, but Husk Power stands out as a low-cost developer

Leading academic groups

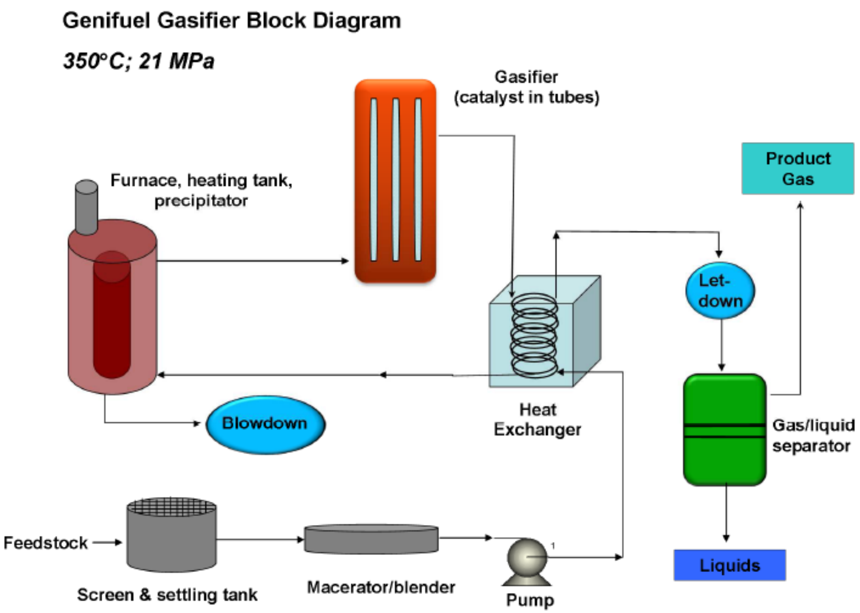
- Most groups work on advanced gasification technologies (see references in Appendix)
- Indian Institute of Technology, Delhi – see link 1 and link 2

Companies

- **Husk Power** – intriguing low-cost gasifier technology deployed at 70 sites in rural Bihar, India
  - Homogenous dry feedstock of rice husks (also corn stover, grasses, or straw); must be <10% moisture
  - Conventional wisdom was that rice husks were low density fuel, and gas emissions had high tar content
  - Downdraft gasifier runs for 16h/day in "single" fuel mode, and has daily cleaning cycle of generator engine
  - Costs $1.2/W installed → 50 kW generator costs $60,000. Remarkably low cost
- MaxWest Environmental Systems – gasification systems that convert wastewater residuals to energy
  - Raised $19 million and is building two facilities (165 ton/day and 1000 ton/day) in China
  - See interview notes in appendix
- **Genifuel Corp** – wet gasification with catalyst bed; 70% - 97% water input possible, so doesn't need drying
  - $1 million CapEx to build 10 ton/day 100 kW facility; can generate electricity at $0.10/kWh – $0.12/kWh
- **Agnion** – Indirect gasifier converts biomass, including sludge, to syngas.
  - Complex process: uses metallic fluid heat pipe for internal heat exchange
  - High capex/low opex model less suited to developing nations
  - $3.5M capex for 8 ton/day facility.
  - Not net energy positive – requires 1.3 MW of heat input, producing 380 kW elec and 630 kW heat
- Several companies developing large-scale plants include Enerkem, Ze-Gen, Fulcrum, Solena, etc.

Most commercial gasifier and pyrolysis systems are complex early-stage technologies ill-suited for the developing world

- These pictures depict the [Genifuel process], and are included here to convey the complexity of a typical fluidized-bed gasification systems. In fact, Genifuel's process is one of the most compact and inexpensive systems being commercialized, and is intriguing from the standpoint that it accepts wet feedstock. However, it costs $1 million CapEx for a 10 ton/day facility, and the complexity is far beyond a sustainable solution for the developing world.
- See Appendix for a case study of a plasma gasification system.



Skid mounted:

Trailer mounted:

Pyrolysis

A mobile pyrolysis reactor from Agri-Therm

A simple pyrolysis kiln

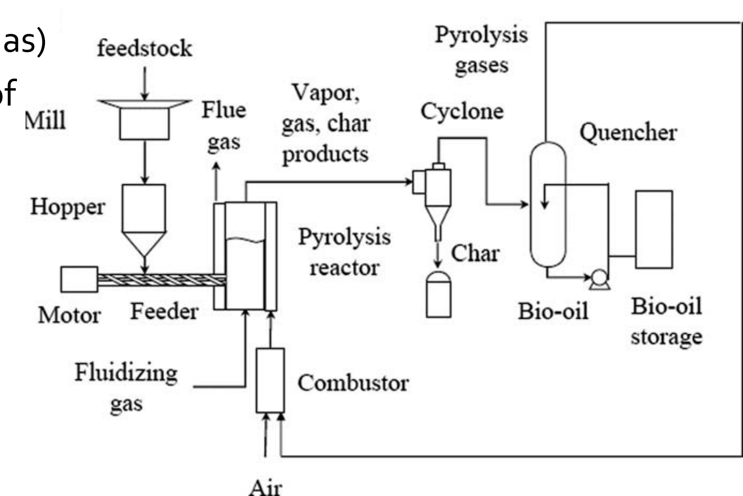
Image: http://biocharfarms.org/farming/

Image: http://biochar.info/biochar.CarbonZero-Experimental-Biochar-Kiln.cfml

Pyrolysis is similar to gasification, but is distinguished by generation of bio-oils and chars rather than gaseous fuels

- **Lux Research take –** high technical risk, and we are skeptical that simple, cheap reactors can be built that would have any advantages over gasifiers. Moreover, the failed commercial attempt of Enersludge in Australia does not bode well.
- **What you need to know**
  - Thermal treatment process in which sludge or other biomass is heated in the absence of oxygen. In "fast" processes, the produced vapors are condensed to form bio-oil, whereas "slow" processes generate biochar for fuel or soil conditioning. The operating temperatures are 350°C - 750°C, and pressures are often several times atmospheric conditions. Some of the vapors and/or char can be combusted to provide heat for the process, in which case the distinction between pyrolysis and gasification becomes blurred.
  - Can produce liquid fuel product, non-condensable gases, solid fuel (char), and water vapor
  - Technology is more immature than gasification – therefore, there could be a higher potential for breakthroughs, but it is further out.
- **Advantages**
  - Produces liquid fuel which can be reused elsewhere (unlike syngas)
  - Both pyrolysis and gasification have more efficient conversion of combustible gases into useful forms of energy than incineration
  - Milder operating conditions than gasification
  - Lower post-process cleaning needs/costs
- **Challenges**
  - Similar to gasification, including complexity and cost (see figure at right).

Typical fast pyrolysis system



Pyrolysis is similar to gasification, but is distinguished by generation of bio-oils and chars rather than gaseous fuels

- Process control more of a challenge than simple gasification. Pyrolysis is inherently multi-stage, requiring optimization of both reactor and quencher conditions, which increases complexity compared to gasifiers.
- Bio-oil quality of fast pyrolysis may vary, require refinement, and be unsuited for engines.
- Quencher requires external source of chilled water

- **Pretreatment** – typically requires dry feedstock, but no special needs otherwise
- **Co-processing and coupling potential** – similar to gasification
- **Technologies**
  - Simple pyrolysis kilns produce biochar for soil fertilizers – slow process requires hours to weeks.
  - Fluidized bed reactors use circulating bed of material (typically sand) to rapidly heat biomass. The gases pass to a condenser chamber, where they are rapidly cooled into liquid pyrolysis bio-oil. Rotating cone reactors are one variant.
  - Hydrous pyrolysis, or hydothermal carbonization (HTC), involves pyrolysis in the presence of water at 180°C – 250°C and high pressure to produce primarily char [Libra et al, 2011]. The technology is very early stage (thusfar it has failed commercially with animal residues) and complex, involving high pressure reactors (~100 atm). Like GeniFuel's wet gasifier, it has intriguing possibilities for fecal sludge, but is many years from realization. As Libra et al assert in their 2011 review, "no experimental work has been published to date on the HTC of sewage sludge."
- **Water content**
  - Like gasification, most processes require dry feedstock (<10% moisture). Hydrous pyrolysis is an exception, but is far from practical realization.
- **Volume**
  - No technical restrictions to scaling down, but economics drive most facilities to larger scale (50+ tons/day).

There are several promising pyrolysis players, but little evidence the technology can be viable in the developing world

- BTG-BTL
  - Uses rotating cone reactor (RCR) to convert biomass to pyrolysis oil
  - Requires under 10% moisture content; claims excess heat can be used to dry feeds up to 55% moisture
  - Feedstock flexible: includes cane bagasse, rice husk, sludge, wood chips (preferred)
  - Bio-oil could be used in industrial boilers, or to replace natural gas
  - $20 million to build 5 ton/hour plant
  - Parent company BTG focuses on basic research around its RCR pyrolysis technology; may be worth engaging to explore interest in CSR development of a low-cost version of its technology
- Re:char –. Low-cost pyrolysis reactors to produce bio-char from corn stover, waste wood, nut shells, & rice hulls. Gaining most traction with its "climate kiln", a simple, slow pyrolysis reactor fabricated from metal barrels
  - Also claims to be developing fast pyrolysis system that will fit in standard shipping container and cost <$10,000. However, no further information is available. Technology is early stage and unproven.
- Ensyn – circulating fluidized bed reactor at 510°C forms oil from mostly forest waste feedstock – lays claim to only commercial operation of fast pyrolysis
- Agilyx - Thermal conversion of waste plastic into synthetic crude oil
- Many literature studies, including:
  - H.J. Park et al., "Clean bio-oil production from fast pyrolysis of sewage sludge", Bioresource Tech. (2010)
    - Use metal oxide catalysts (CaO) to clean chlorine from bio-oil
    - 450°C operating temperature; feed gas heated electrically
    - Accepts sewage sludge with a 5% moisture content (dried separately)

Case study – Enersludge led the way in next-gen pyrolysis technology, but poor quality bio-oil output led to its demise

- Environmental Clean Technologies (Australia) developed the Enersludge process, a pyrolysis technology for conversion of dried sewage sludge pellets at 450° C
- The system produced a solid fuel product (char) and liquid fuel "bio-oil". Char was used for sludge drying, since the process required a 95% thermal solids ratio
- Developed and commercialized over 15 years, and built a full-scale installation in Perth, Western Australia c. 2004 to process 25 dry tons/day; 30% yield by weight of bio-oil. The plant comprised of sludge dewatering and drying, pyrolysis unit, energy recovery, and gas cleaning
- Enersludge promised many benefits, including:
  - Complete energy recovery
  - Phosphorus harvesting
  - Control of pathogens and toxic compounds (heavy metals, chlorine related compounds)
  - Carbon credits
  - Environmentally sound treatment
- The facility shut down after 4 mo. of operation because the oil contained high levels of water and solids and was unfit for diesel engines; company has now abandoned the technology
- **The developing world is a far more demanding setting in terms of cost and reliability, and so the Enersludge experience does not bode well for the technology's viability.** It's possible the bio-oil could find other beneficial uses outside of diesel engines, but controlling oil quality is a large technical barrier.

Thermo-mechanical processing

LaDePa sludge pelletizer in Durban, South Africa

Image: http://forum.susana.org/forum/categories/53-faecal-sludge-management/406-new-sludge-pelletising-machine-in-ethekwini-durban-wins-iwa-award

Thermo-mechanical processing is feasible but energy intensive

- **Lux Research take** – stand-alone thermo-mechanical treatments are energy intensive. They require a steady source of power, like a diesel generator. This is a luxury few developing world communities will be able to afford unless they are already paying tipping fees for sludge disposal and the pelletized sludge fertilizer can be monetized. The technology is feasible, but the economics will need careful consideration. Ideally, sludge can be disinfected via a post-digestion thermal step powered by biogas and/or syngas from gasification.
- **What you need to know:**

Mechanical treatment: It is important to distinguish the type of mechanical treatment: As expressed in the Omni-Processor Vision document, the ideal Omni-Processor would accept all urban-residential wastes. After mechanical maceration, centrifugation, and shredding, it will implement the waste-to-energy technology of interest. **This mechanized approach will likely be capital-intensive, energy hungry, and require external sources of electricity**, all of which may be inconsistent with the demands of a developing world setting.

- All sludge treatment technologies will require some form of pre-filtering to remove large solids, grit, and sand, but this process can be largely gravity fed without need for substantial mechanization.
- These considerations dictate that the fecal sludge should be collected as a separate waste stream rather than mixed with general urban waste. To co-process sludge with selected fractions of organic waste, food residues or animal waste, these separate waste streams can be combined as needed.

Thermal treatments: pre-treatments have the advantage that they can be coupled to anaerobic digestion, facilitating more rapid organic breakdown and larger biogas generation. They also dewater the waste, aiding subsequent drying steps. However, most are unfeasibly complex processes, and require high pressure/ high temperature reactors. Post-treatments (like LaDePa) are simple and feasible, but are energy intensive and therefore expensive to operate unless offset by avoided sludge tipping fees or sludge fertilizer revenues

Consider thermo-mechanical processing when avoided sludge tipping fees can offset the energy costs

Process description

- Post-treatment: sludge from a digester or pit latrine is passed through a thermal pelletizer to reduce the sludge volume and render it in a form suitable for soil fertilizer. Sludge is ground up, and its temperature is raised to 100+ C for several minutes.
- Pre-treatment: Pre-treatments such as thermal hydrolysis use a high temperature (150 C – 180C), high pressure (6 – 10 atm) injection of steam into biomass in an enclosed reactor for 0.5 h – 1 h. This destroys (lyses) the cell walls in sludge, allowing a more rapid, complete digestion and sterilizes the waste by destroying bacteria that are present. Technology developers include Cambi and Veolia Water.

Advantages

- Thermo-mechanical post-treatment kills pathogens, rendering sludge dry and inert and suitable for soil fertilizer as an EPA class A bio-solid.
- Pre-treatments like thermal hydrolysis accelerate digestion and promote the formation of biogas

Challenges

- Post-treatment is effective but not a primary fecal sludge treatment technology – it accepts output from pit latrines, digesters, or drying beds. It also requires substantial energy inputs.
- Thermal pre-treatment technologies are sophisticated and capital intensive

Water content and volume – typically accepts partially dried sludge (from drying beds or latrines), but no technical limitation on wet feedstocks (requires much more energy); effective at small scale.

Key developers

- For low-income countries, two developers are LaDePa and an academic group that reported this project in Faisalabad, Pakistan. As with the other approaches, there are several technology developers aiming at rich-world markets with solutions that are likely unfeasible in a low-income country. One developer of turn-key pelletizer systems for North America is Redona.

Incineration is a faded star inappropriate for small decentralized treatment units

- **Lux Research take:** Incinerators are high-cost, large-scale, and potentially environmentally harmful if emissions and ash are not effectively treated. It is not appropriate for an urban setting in the developing world. As agreed with the BMGF, we did not include this as a primary research area for the project.
- Incineration with energy recovery aims at complete oxidation of the sludge at high temperature
  - Needs mechanically dewatered or dried sludge (like gasification and pyrolysis)
  - Environmental problems include exhaust gas emission and ash quality, but standard technology exists to scrub emissions, and high temperatures can immobilize heavy metals with inorganics in ash
  - Expensive exhaust gas treatment is the main cost driver
  - Mainly large-scale, centralized facilities
- Stand-alone plants are very costly; there is some effort to co-incinerate sludge in a coal-fired power plant, but this is impractical at a community scale
- The literature is unambiguously pessimistic about the prospects of incineration for sludge waste disposal
  - New England Interstate Water Pollution Control Commission: "A sludge incinerator is a very mechanized and capital-intensive investment that must be managed with a high level of expertise and attention to maintenance." Sites within 0.5 miles of residential neighborhood are poor candidates for incineration facilities
  - Nelson et al. (2008): "Even when coupled with energy production, however, sludge incineration requires a net input of energy to dry the sludge. The capital costs can also be prohibitive."
  - Moustakas et al. (2008) report gasification is 30% - 50% less costly than incineration
  - Ferrasse et al. (2003): "Comparison of the economical costs of the different conventional processes clearly demonstrates that incineration is slightly more expensive than other methods."

Agenda

- Overview and Methodology
- Review of processes
  - Comparative analysis
  - Anaerobic digestion
  - Gasification
  - Pyrolysis
  - Thermo-mechanical treatment
- Technology deep dives
  - Fixed-bed gasifier
  - Fast pyrolysis
  - Upflow anaerobic sludge blanket
- Quantitative analysis
  - Ranking candidate technologies
- Interview insights
- Recommendations

Technology focus

- Amongst the four sludge treatment processes, we identified the most viable technologies for the developing world, and analyzed them across the following dimensions to establish a quantitative basis of comparison
  - Technical strength:
    - Technical merit for fecal sludge treatment
    - Cost potential
    - Scalability to target size
    - Complexity
  - Feasibility
    - Applicability for developing world
    - Potential for co-processing
    - Maturity
    - Potential for valuable end products
    - Inputs/outputs: Implications for energy and water inputs, and post-treatment needs
- The scores for all technologies are detailed in the accompanying Excel file.
- Here we highlight three technologies for deeper dives:
  - Down-draft gasifier
  - Fast pyrolysis
  - Upflow anaerobic sludge blanket + thermal post-treatment

Fixed-bed gasifiers are the oldest and simplest gasifier technology, and as such are the most viable in their class

- Description:
  - simplest gasifier technology – most feasible is down-draft version, in which fuel/gas move same direction down through reactor
- Logistical needs
  - Requires pelletized dry fuel with density > 270 kg/m^3
  - Engine to burn syngas and generate electricity, and a battery or other form of fuel to start up the motor and the pump (which drives the gas flow in the gasifier)
  - System can start up in minutes, and is relatively simple to control.
  - High process temperatures 600 C - 1100 C
- Advantages
  - **Downdraft**: produces relatively tar-free gas suitable for direct burning in an engine. Improved environmental footprint compared to updraft, which has a higher tar content.
  - **Updraft**: higher operating temperature translates to higher permissible moisture content and more toxins/heavy metals destroyed and immobilized
- Challenges
  - **Downdraft**: low-density materials cause flow problems and high pressure drop; solid fuel must be pelletized prior to use; slagging problems with high ash content fuels; lower efficiency compared to updraft due to less internal heat exchange; downdraft needs uniform high temperatures, so impractical above 350 kW.
  - **Updraft**: potential for tar-containing emissions and higher explosion risk. Higher temperatures increase complexity and CapEx

Fixed-bed gasifiers are the oldest and simplest gasifier technology, and as such are the most viable in their class

All scoring on scale of 1 – 5 (weakness to strength)
See Appendix for details of scoring rubric.

Technical strength

Technical merit for FST	3	Only a partial solution, since it requires dry feedstock, but process heat could help dry the sludge.
Cost potential	4	1 ton/day facility will cost ~$100k to $200k CapEx
Scalability to target size	5	Small gasifiers like Husk Power's consume 300 kg to 500 kg per day, and generate 35 kW to 50 kW of electricity
Complexity	3	Requires trained technicians to operate and maintain gasifier and electrical generator, but no more complicated than vehicle mechanics.

Feasibility

	Applicability to developing world	3	Suited to electrification schemes which directly use syngas on-site to power a generator. Simpler and less expensive than fluidized bed gasifiers.
	Co-processing potential	3	Provided fuel is dry, pelletized, and sufficiently dense (> 270 kg/m3), multiple feedstocks can be co-processed. However, urban slums are likely to have wet organics like food residues, rather than dry agricultural waste.
	Maturity	2	Simple fixed-bed gasifiers have been around for 100+ years , but limited experience in gasifying sludge.
	Potential for valuable end products	4	Can generate heat or electricity, but syngas difficult to capture and transport, so likely most suited to electrification (requires gas-powered generator). Biochar residue useful for soil additive.
Inputs/ outputs	**Post-treatment**	4	Emissions control can be a challenge and add to the cost, but sludge treatment is complete
Inputs/ outputs	**Energy inputs**	3	Requires start-up energy to set motor/pump in motion. Husk Power uses a battery pack for start-up. In steady-state operation, the process is net energy positive. Feasible for electrification schemes.
Inputs/ outputs	**Water ratio**	1	Requires <20% dry feedstock, or process cannot be sustained without external heat input. Genifuel Corporation offers a wet gasification process (70+% moisture content of input), but the process is likely unfeasible in cost and complexity.

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Fast pyrolysis is trickier to manage than pure gasification and so there is higher technical risk

- Description:
  - Process very similar to fluidized-bed gasification, except oxygen is completely excluded from the reactor chamber. Pyrolysis occurs in a few seconds and produced vapors are rapidly condensed into bio-oil rather than combined with oxygen to generate syngas (as in gasification); produces liquid fuel product, solid fuel (char), water vapor and other gases; may involve a rotating cone reactor (e.g. BTG-BTL) or cyclone separator
- Logistical needs
  - Similar to fluidized-bed gasification but lower temperature demands (350C - 750C)
  - Need control equipment to manage load response and tar content of gases; fuel pellets must be smaller (< 1 inch); suited for greater than 500 kW power, and typical scale is much larger
- Advantages
  - Lower operating temperature than gasification is advantageous in terms of reactor design
  - Produces liquid fuel and biochar, a potential soil improver
- Challenges
  - Complexity and cost
  - Maintaining the delicate balance between adding enough heat to pyrolyze the feedstock without overheating and gasifying it could be tricky
  - Bio-oil may be unsuited for engines (this is the main reason for the failure of Enersludge, a commercial scale pyrolysis facility in Australia)
  - Some concern about potential for polyaromatic hydrocarbons and dioxins in biochar

Fast pyrolysis is trickier to manage than pure gasification and so there is higher technical risk

All scoring on scale of 1 – 5 (weakness to strength)
See Appendix for details of scoring rubric.

Technical strength

Technical merit for FST	3	Only a partial solution, since it requires dry feedstock, but process heat could help dry the sludge. Some literature demonstrations in WWTP, but long shot for developing world
Cost potential	3	Reactors similar to fixed- or fluidized-bed gasifiers but operating at lower temperature. Needs a condenser to cool gases, but no need for engine or power-generating equipment to burn and convert syngas.
Scalability to target size	5	Pyrolysis has been demonstrated at < 1kg scale up to many tons/day scale
Complexity	2	Pyrolysis conditions could be more challenging to maintain than those in a gasifier; e.g. particle sizes too large undergo incomplete pyrolysis due to insufficient heating, and too small ones may overheat and gasify (Park et al., Bioresource Technology, 2010)

Feasibility

	Applicability to developing world	3	Most commercial efforts too large and costly, but the considerable interest in generating bio-char from ag waste for soil improvement in the developing world (e.g. re:char) could spill over into sludge treatment
	Co-processing potential	3	Similar co-processing potential to gasification. Experiments have been carried out to investigate pyrolysis with municipal solid waste and garden waste (e.g. see Shen et al, Fuel 2005)
	Maturity	1	Limited to lab-scale academic endeavors; large-scale commercial effort in Australia, Enersludge, failed
	Potential for valuable end products	5	Generates liquid fuel, which is more fungible (and portable) than syngas, but quality for engine burning can be suspect
Inputs/outputs	**Post-treatment**	3	Because gases are not burned, requires a way to capture or clean the non-condensable gases. Some literature studies use an electrostatic precipitator, but this may not be feasible in a resource poor setting.
Inputs/outputs	**Energy inputs**	2	Reactor needs start-up energy, similar to gasifiers. In addition, needs a condenser (e.g. with chilled water loop) to condense vapors, requiring extra pump energy and water supply
Inputs/outputs	**Water ratio**	1	Requires <10% moisture fraction feedstock. Char could be used as a heating fuel to dry sludge (if not as a soil fertilizer).

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UASB and thermal post-treatment completely treats sludge and can be self-powered; sludge volume remains an issue

- Description of Upflow Anaerobic Sludge Blanket (UASB) digesters:
  - Wastewater passes upwards through a "blanket" of bacteria housed in a reactor vessel. The resulting anaerobic degradation process generates biogas containing CH_4 and CO_2. The upward motion of released gas bubbles causes hydraulic turbulence that provides reactor mixing without any mechanical parts. At the top of the reactor, the water phase is separated from sludge solids and gas by a separator.
  - In an article, "Thermal hygienization of excess anaerobic sludge," Borges et al. show that excess (digested) sludge from a mesophilic UASB (23°C) that is heated in a separate thermal reactor to 70°C for 60 minutes can fully inactivate *Ascaris lumbricoides* (helminth) eggs (see Appendix); the thermal energy is supplied by the UASB-generated biogas [Borges, 2005]. A separate study shows increased thermal disintegration of sludge and 50% increase in biogas generation [Borges, 2009]. Results are significant because most prior art studied the effect of 160°C – 180°C pre-treatments, which entails significantly higher investment and OpEx.
- Logistical needs
  - Near-neutral pH. a constant temperature (35°C – mesophilic, or 55°C – thermophilic), and a relatively consistent feeding rate. Footprint can be as small as 0.03 m^2/person. Hydraulic residence times are typically 12 – 20 days. Start-up can take up to two months to fully establish the microbial colony.
- Advantages (see also p. 11)
  - Very low complexity unit with no moving parts → low CapEx and OpEx. Compact, small footprint device that operates continuously (not well suited to batch operation)
- Challenges:
  - More complex logistics in terms of maintenance of a separate thermal reactor, and thermal regulation needed to maintain elevated temperature and manage the accelerated process. If microbial colony is lost, reactor can be down for 1 – 2 months while population is reseeded. This could be overcome by operating a larger number of smaller units with some redundancy built in.

UASB and thermal post-treatment completely treats sludge and can be self-powered; sludge volume remains an issue

All scoring on scale of 1 – 5 (weakness to strength)
See Appendix for details of scoring rubric.

Technical strength

Technical merit for FST	4	Complete treatment for sludge (but sludge volume remains); water requires secondary treatment, such as a trickling filter.
Cost potential	4	Marginal increase over standard UASB due to need for gas burner(s) and some form of thermal control
Scalability to target size	5	Can serve communities of 500 to 1 million inhabitants
Complexity	4	Single stage UASB reactors are almost maintenance-free, with no moving parts. Easily the least complex technology. Process may need some control to maintain temperature and pH, and to introduce seed population at start-up. Post-treatment entails slight increase in complexity due to separate thermal reactor

Feasibility

Applicability to developing world		4	Low CapEx, low OpEx sludge treatment option that is simple to operate and has been proven out in Brazil
Co-processing potential		4	Viable to co-process with animal waste or other organic waste such as food residue. These fractions can help stabilize the fecal sludge process; on the flip side, adding fecal sludge can promote a favorable C:N ratio lacking in organics, creating a mutually beneficial scenario. Establishing reliable mix and feed rates will be a challenge
Maturity		4	UASB is a mature technology for sludge treatment, but thermal post-treatment is only at demo scale
Potential for valuable end products		3	Maintaining higher temperature will consume most or all of generated biogas ; sludge can still be dewatered and dried for soil additive
Inputs/ outputs	**Post-treatment**	4	Demonstrated to effectively remove helminth eggs (*Ascaris lumbricoides*), which are one of most resilient sludge pathogens
	Energy inputs	4	May be self-sustaining on UASB biogas alone
	Water ratio	4	Flexible technology; 55% - 75% water fraction typical for single-stage reactors; higher water fractions (80+%) possible, but will require a larger reactor footprint (but more suited for more complex two-stage reactor)

Agenda

We quantitatively analyzed the leading technologies to generate the Lux Innovation Grid (LIG)

		Fixed-bed gasifier	Fluidized-bed gasification	Plasma gasification	Fast pyrolysis	Incineration	UASB	UASB/ Trickling filter	UASB/ Thermal treament	LaDePa
	Weight	Score (1-5)*	Score (1-5)	Score (1-5)	Score (1-5)	Score (1-5)	Score (1-5)	Score (1-5)	Score (1-5)	Score (1-5)
Technical merit for FST	25%	3	3	3	3	4	2	3	4	3
Cost potential	25%	4	1	1	3	1	5	4	4	2
Scalability to target size	25%	5	1	1	5	1	3	5	5	5
Complexity	25%	3	2	1	2	2	4	4	4	3
Technical value		**3.8**	**1.8**	**1.5**	**3.3**	**2**	**3.5**	**4**	**4.3**	**3.3**
Applicability for developing world	20%	3	1	1	3	1	4	4	4	5
Potential for co-processing	20%	3	3	4	3	5	4	4	4	1
Maturity	20%	2	1	1	1	4	5	4	4	4
Potential for valuable end products	20%	4	3	2	5	2	5	5	3	4
Inputs/Outputs	20%	2.7	2	2.3	2	1.7	3.3	3.7	4	3
Post-treatment		4	3	4	3	2	2	3	4	5
Energy		3	2	2	2	1	4	4	4	1
Water ratio		1	1	1	1	2	4	4	4	2
Feasibility		**2.9**	**2**	**2.1**	**2.8**	**2.7**	**4.3**	**4.1**	**3.8**	**3.3**

* See Appendix for scoring rubric

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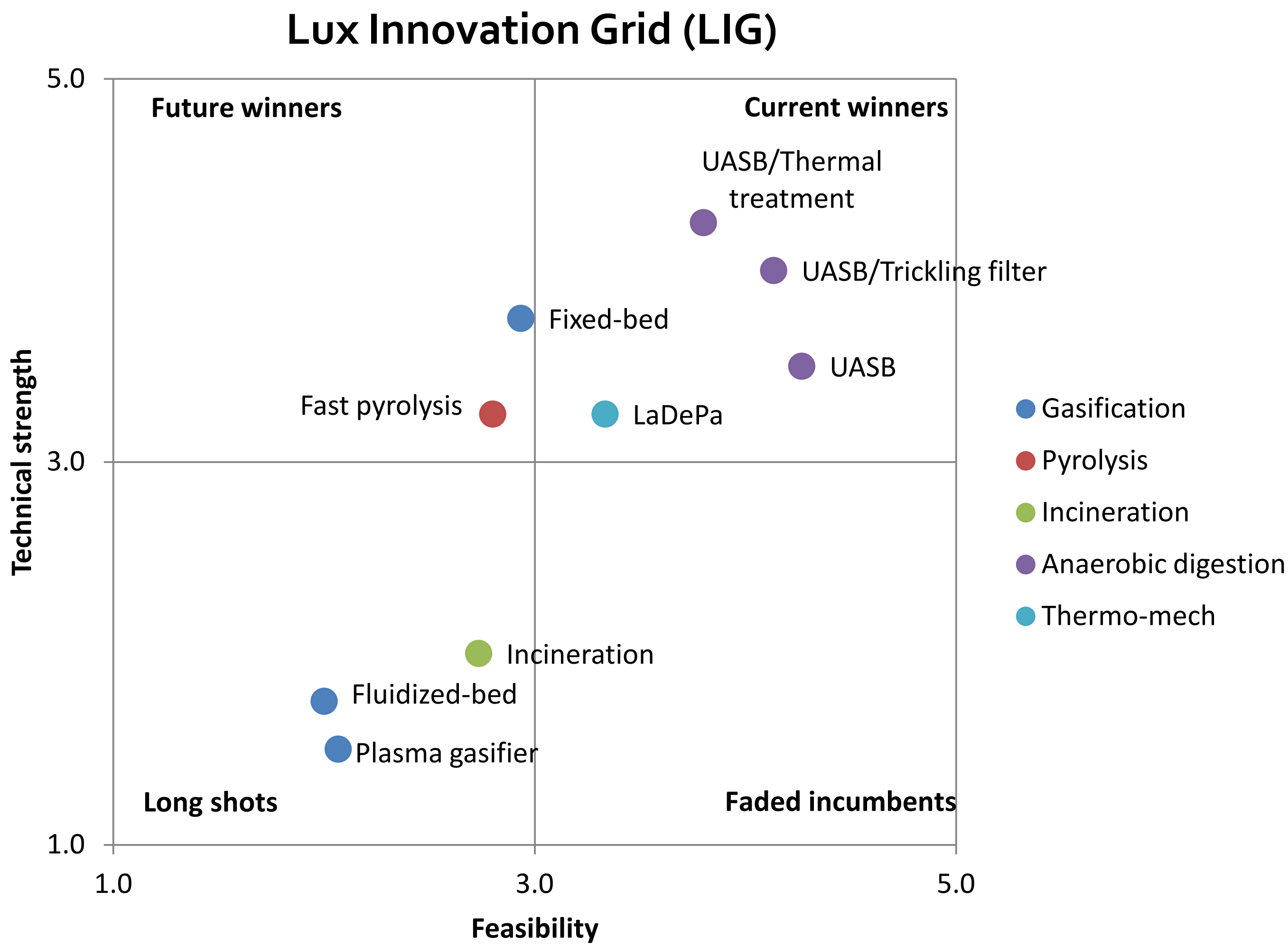
On the LIG, anaerobic digestion (UASB) dominates today, while LaDePa also proves its viability. Fixed-bed gasifiers could emerge, while fast pyrolysis is a longer shot



Anaerobic digestion (UASB) dominates today, while LaDePa also proves its viability. Fixed-bed gasifiers could emerge, while fast pyrolysis is a longer shot

- The current winners are dominated by anaerobic digestion. A pervading theme throughout both our interviews and the literature on sludge technologies viable for the developing world was that anaerobic digestion is the clear technology of choice. To be sure, it is not a complete solution. However, recent studies from Brazil have shown that thermal post-treatment can help solve the pathogen problem, and the supernatant (wastewater) can be aerobically treated at low cost with trickling bed filters.
- LaDePa is a thermo-mechanical sludge treatment process proven in South Africa, and therefore a current winner. Its Technical Strength score is reduced by its high OpEx (diesel generators or electricity required) and the fact that it requires primary sludge treatment solutions, such as pit latrines, digestion, and/or drying beds. Its feasibility score is solid but compromised by the lack of co-processing potential and negative energy balance.
- To our knowledge, there is no real-world demonstration of low-cost gasification of dried fecal sludge. However, if we look to the adjacent domain of agriculatural residue gasification, we are very encouraged by the traction of Husk Power. Its example is highly relevant to the BMGF, and we recommend engagement. This example combined with the long track record of the technology places down-draft gasification in the future winners category.
- Fast pyrolysis is penalized by its relative complexity compared to down-draft gasification and its immaturity. Process conditions can be tricky to manage, and there is no evidence of low-cost development of the technology. Much hype has surrounded slow pyrolysis to treat crop waste and generate biochar, but as yet this technology is unproven for sludge treatment.
- Long shot technologies such as plasma and fluidized-bed gasification and incineration are those which are too complex. This complexity is a show-stopper in its own right, but it also leads to high capital expenditure, which in turn translates to the need for large scale facilities to give the necessary economies of scale. Therefore, we are doubtful these will ever be viable in a developing world urban setting.

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  - Fast pyrolysis
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- Interview insights
- Recommendations

Interview insights

- We interviewed 7 experts in developing world sanitation and sludge treatment technologies:
  - At present, there is little commercial interest in the challenge of developing world sludge treatment due to the difficulty of creating profitable businesses in this setting. Therefore, most experts are based in academic institutions. In particular, Brazilian researchers stand out as thought leaders in the space.
  - One notable commercial enterprise is Husk Power. Although Husk is not working on sludge treatment technology, it is making great strides in its efforts to electrify rural Bihar in India through gasification of rice husk waste. The technical challenges and strong cost constraints Husk faces are highly applicable to the Omni-Processor project.
- General issues
  - Necessary to develop **small and simple treatment processes**/ facilities that do not require highly-skilled people to operate
  - Changing people's behavior related to waste is as much, if not more, of a challenge than the technology
- The consensus amongst all interviewees: **the most appropriate sludge treatment technology for a developing world setting is anaerobic digestion (AD).**
  - Passive technology with no mechanical parts – simple operation
  - Thermophilic digestion (at 50 C) for 30 min. is sufficient for most pathogen inactivation, although the process conditions (e.g. pH, temperature) are harder to control, and this will require more energy inputs
  - Brazil, Columbia, Mexico, and India are well advanced in using AD for domestic wastewater

Interview insights

- Device footprint will be determined by the water fraction – important to minimize (e.g. through source separation of waste)

- Nearly complete treatment of anaerobic digestion sludge can be accomplished through:
  - Trickling filter, aerated biofilter, or stabilization ponds (note that trickling filter systems can be relatively small footprint); in Brazil, they have achieved >90% BOD with UASB + trickling filter combination
  - Composting or thermal treatment using energy from combusted biogas
  - Pre-treatment to raise pH so natural ammonia in urine kills some pathogens could be possible

- Pyrolysis and gasification
  - Complexity of operation is a concern
  - Have the potential to be net energy positive, but **concerning lack of real-world data on the energy balance** → technical risk of immature technologies
  - One interviewee advocated gasification over pyrolysis, perhaps because it's a more mature technology for converting dry agricultural and wood waste
  - Any biomass can be gasified, but it must be dry (< 10% moisture). Husk Power relies on natural drying for crop residues. Could re-use waste heat for drying (or use biogas from a digester), but this would make the process a bit more complex

Interview insights

- Down-draft gasifier process is not highly sensitive, provided moisture content is low (<10%) and density is sufficient (> 270 kg/m^3)
- Tar cleaning of emissions is a challenge, but one that can be solved (Husk cleans its engines daily)
- Also, engines need to be modified to burn syngas (which has fractions of CO and H_2O)
- MaxWest Environmental, a gasifier developer rolling out systems in China, doesn’t see any competitors pursuing pyrolysis, but it is aiming at large-scale plants (>100 tons/day)

Co-processing feasibility

- Feasible to add organic fraction to anaerobic digester; this is done in Sweden (and there are various literature studies)
- Food waste has ~90% moisture fraction, which is well-suite to AD, but there are some challenges of methanogenesis of pure food waste, so combining it with sludge organics is good. High fat content is ideal
- Adding animal waste to human waste likely improves stability of AD process – easier to get the correct C:N ratio in the digester (assuming that not all animal urine is harvested); however, co-processing inputs depend on geography and behavioral factors
- Downdraft gasifiers (such as Husk Power’s) can accept a mix of inputs, assuming moisture and density are appropriate

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Lux Research recommends anaerobic digestion coupled with gasification or thermal pelletization as a promising path to a complete fecal sludge solution for the developing world

- As a low-cost, small-footprint, and simple technology, **anaerobic digestion must surely be one part of the Omni-Processor solution.**
  - The generated biogas can be used in a thermal post-treatment step to inactivate pathogens present in the sludge and any surplus could be used for drying
  - The simplest reactor type is the upflow anaerobic sludge blanket (UASB), which operates at relatively high water fractions in a continuous fashion; in tandem with a trickling filter and thermal post-treatment, this technology presents a complete solution
  - AD is viable for (and likely improved by) co-processing with organic waste, esp. food waste with a high fat content
- Gasification cannot be a stand-alone fecal sludge treatment technology due to its strict demand for dry feedstock. Large-scale sludge gasifiers are highly complex and costly, but **a simple down-draft gasifier could be developed for dried sludge feedstock, and would effectively complement the primary UASB treatment**
  - The syngas could be burned to power an electrical generator – e.g. for an electrification scheme – and the waste heat would contribute to feedstock drying
  - Residual char is rendered inert and may be an effective soil additive
- Stand-alone thermal-mechanical treatments require substantial energy inputs, and are thus best suited to areas where sludge tipping fees can subsidize the OpEx (e.g. LaDePa in eThekwini pays $2 million/year for sludge disposal). However, they are proven and viable in the developing world, if the economics can be managed.
- Fast pyrolysis is attractive in generating a liquid fuel, but the technical risk is high, and we are skeptical that simple, cheap reactors can be built that would have any advantages over gasifiers. Moreover, the failed commercial attempt of Enersludge in Australia does not bode well.

The BMGF should engage the following thought leaders and companies

- Brazilian academic groups lead the way in developing low-cost anaerobic digester technologies as evident from the quality and relevance of their published research. Engage the following experts:
  - Prof. Carlos Chernicharo – Dept. of Sanitary and Env. Engineering, Federal University of Minas Gerais, Brazil
  - Prof. Eduardo Pacheco Jordao – Federal University of Rio de Janeiro
- For experts in developing world sanitation technologies, engage
  - Prof. D. Mara – Prof. of Civil Engineering, University of Leeds
  - Prof. Marcos von Sperling – Dept. of Sanitary and Env. Engineering, Federal University of Minas Gerais, Brazil
  - Prof. Wim Rulkens – Wageningen University
  - Prof. Kartik Chandra – Columbia University (already engaged with the BMGF)
- Companies :
  - Husk Power – low-cost gasification for rural electrification in India
  - Re:char – slow and fast pyrolysis reactors (already engaged with the BMGF)
  - LaDePa – thermal pelletizer for sludge post-treatment
  - Clearford Industries – distributed AD sewage systems with biogas production for the developing world
- There are dozens of companies operating in these technology domains for rich world markets, but we hesitate to recommend any for partnerships given the vastly different application needs. Some of the leading players are:
  - Anaerobic digestion: Harvest Power, Cambi, AAT, Onsite Power
  - Gasification: MaxWest Environmental Systems, Genifuel, Agnion, Enerkem, Fulcrum
  - Pyrolysis: BTG-BTL, Ensyn, Agilyx
  - Thermo-mechanical: Redona

Appendix

- Scoring rubric for Lux Innovation Grid
- Case study of plasma gasification
- Case study of anaerobic digestion co-processing with MSW
- References

Scoring rubric for Lux Innovation Grid

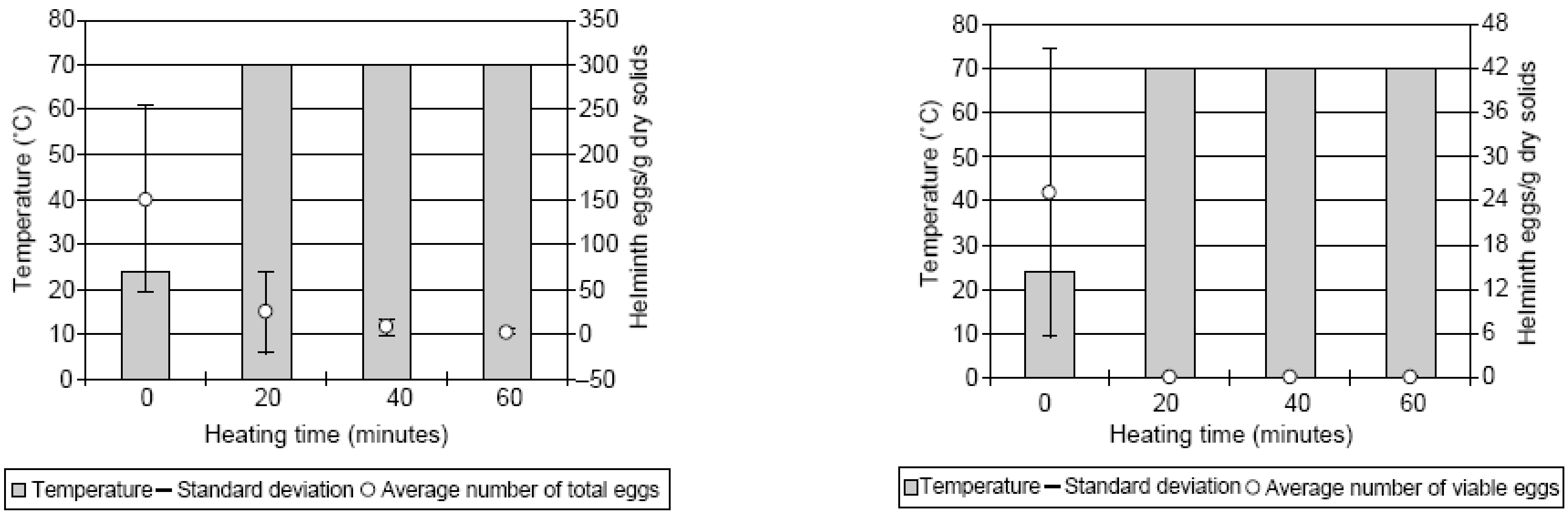
Technical strength

Technical merit for fecal sludge treatment	1 - poor 3 - somewhat effective, but add'l processing required 5 - complete treatment
Cost potential	1 - $100+/person/yr (High) 3 – Medium cost 5 - < $15/person/year (Low)
Scalability to target size	1 - large scale only 3 - 1 ton/day - 5 tons/ day possible 5 - scale independent
Complexity	1 - highly sophisticated apparatus 3 - trained staff could operate and repair; some expertise needed 5 - low-tech

Feasibility

Applicability for developing world	1 - Inappropriate 3 - Moderate applicability with some gaps 5 - Highly appropriate (robust operation, low cost, small scale)
Potential for co-processing	1 - Poor - inflexible process 3 - Feasible under some conditions 5 - Co-process improves efficacy and is already practiced
Maturity	1 - > 3 years to commercial deployment 2 - small demo 3 - pilot 4 - introduction 5 - scale
Pre-treatment/other inputs	
Material/chemicals	1 - many inputs needed 3 - some inputs required 5 - none
Energy	1 - continuous external energy required 3 - external energy needed for start-up (or intermittently) 5 - process completely self-energized
Water ratio	1 - extensive drying required (<10% TSS) 3 - some dewatering needed (< 40% TSS) 5 - wet process
Potential for valuable end products	1 - none 3 - some revenue generation may be possible 5 - high

Helminth egg inactivation from thermal post-treatment of excess sludge from an UASB digester



- Data show that after 20 min. of heating at 70°C, there is a significant reduction in number of helminth eggs (40/g to 15/g). Of the eggs found, none was found to be viable. After 60 min. of heating, the number of eggs is also reduced to zero, likely due to disintegration.
- From Borges et al., 2005. (see references).

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Case study – plasma gasification

- A. Mountouris et al., “Plasma gasification of sewage sludge”, Energy Conv. and Management **49**, 2264 (2008).
- Process is net energy positive
- Claim much lower air emissions and leachate toxicity than incineration. Tars, char, and dioxins are broken down due to high energy process; however, the process is complex, especially related to emissions management:
  - Gas-cleaning sub-system after main furnace to eliminate acid gases, particulates, heavy metals, and moisture
  - Water quench, packed bed tower scrubber, venturi scrubber, H_2S absorber, filters to entrap heavy metals and other fine particles
- Net electrical energy production depends on:
  - Moisture content, air/oxygen, gasification energy, net thermal balance
  - Quality of heating gas, reactor temperature (1000 C)
- In theory, produces net 2.85 MW of electrical energy (4.2 MW total, with 1.35 MW fed back to furnace)
- Requires large amount of energy – 4.6 MW – to dry sludge; in theory fully self-generated

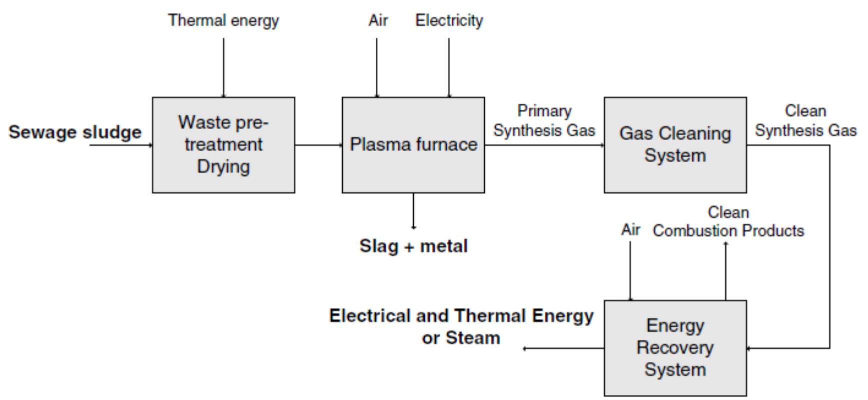

Fig. 1. Block diagram of plasma gasification process.

Case study – co-processing of organic MSW and sludge can be synergistic

- See G. Bujoczek et al., "Co-processing of organic fraction of MSW and Primary Sludge", Env. Tech **23**, 227 (2002).
- Typically, the carbon-to-nitrogen (C:N) ratio is too high in MSW for effective digestion; sludge addition can be beneficial to balance C:N.
- Adding sludge allows a faster start-up due to presence of acclimated anaerobic bacteria
- Improves process stability – through addition of sludge and/or manure
- Enhances biogas production rate
- Reactors that did not receive sludge addition suffered incomplete digestion of MSW
- Adding sludge increases ammonia content (NH_3), which can be a beneficial nutrient but also toxic: if $pH > 8$, it can inhibit bacterial activity
- Note that retention times were 30-days in the study

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Thank you

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