HyBrTec® Biosolid-to-Hydrogen
North East Residuals & Biosolids Conference

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Speaker Introduction – Melahn Parker

- **Dr. Melahn L. Parker**, **President & CTO** has a decade of experience analyzing, modeling, engineering and fabricating complex energy systems.
- Graduated Stanford University 2009 with a Ph.D. in Aeronautical Engineering, Caltech 2003 with an M.Sc. in Chemical Engineering, M.I.T. 2001 with an M. Eng. in Aerospace Engineering, and M.I.T. 2000 with B.Sc. degrees in Aerospace & Chemical Engineering.
- Worked at DNV GL, McKinsey & Company, Sandia National Laboratory, Northrop Grumman Corporation, and the Boeing Company; in addition to directing the research and development of the Chemergy processes.
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Why Chemergy is at NE Residuals & Biosolids Conference

- Preparing to pilot our HyBrTec process to convert biosolids-to-hydrogen
  - Moving the proven science into practical engineering to eliminate both biosolids and plastic waste in a net-negative or carbon-neutral basis, cost-effectively, and at scale

- We're here to:
  - Network with experts in biosolid utilization,
  - Identify funding to support our work,
  - Find WWTP sites able to host a demonstration, and
  - Meet technology partners interested in supporting our R&D

Problems – Biosolid Disposal & Clean Energy

1. Treated sewage or “Biosolids” are a burden
   - Biosolids are subject to increasing regulations and contain harmful chemicals:
     - pharmaceuticals, hormones, pathogens, bacteria, viruses, protozoa and parasitic worms, as well as heavy metals like lead, cadmium, arsenic, mercury, and PCBs, PFAS, dioxins, BPAs, etc.
   - Landfills are oversubscribed and land spreading is being limited/stopped
   - WWTPs now pay from $40-$120 per wet ton to dispose of their biosolids (growing +10%/year)
2. Decarbonizing transport and industry is a challenge
   - Fuel cell vehicles are being commercialized, but need affordable distributed hydrogen fuel
   - Renewable hydrogen is prohibitively expensive at ~$6 per kilogram which limits its adoption
3. Expansion of renewable electricity is constrained
   - Intermittent wind and solar suffers power curtailment as it is further adopted
   - Energy storage economics are penalized by low utilization

Key advantages of HyBrTec® in addressing problems

1. Biosolid waste elimination
   - Reacts with 50% wet waste, thereby reducing the need to dry it[1]
   - Removes organic components and concentrates inorganics for easier disposal or recycling
   - Sterilizes waste to eliminate pathogens and other persistent chemicals

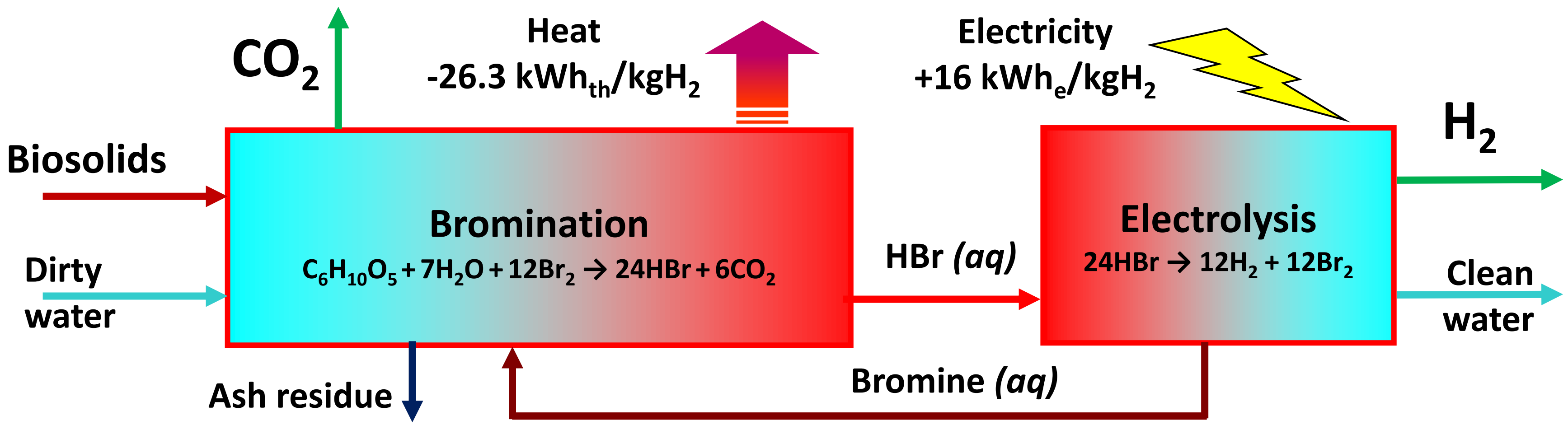
2. Decarbonize transport and industry
   - Requires half the electrical energy of water electrolysis, thereby allowing the production of twice as much hydrogen from the same electric resource[2]

3. Economical electrical energy storage “option”
   - Operates 24-7 to maximize asset utilization in most economical mode that the market demands, discharging electricity when power is expensive and making hydrogen when power is cheap

1. Sufficient waste heat from process is available to dry from 75 wt% water to the 50 wt% water desired for reaction;
2. Forecasts project electricity to be 50-80% of the cost of hydrogen, so reducing the electricity required has a significant impact on final hydrogen production cost;

HyBrTec® process

- Produces hydrogen from biosolids
  - Oxidizes wastewater & biosolids with bromine (Br_2) to produce hydrobromic acid (HBr_{aq}) and carbon dioxide (CO_2), and release heat
  - HBr_{aq} is electrolyzed to recover green hydrogen and recycle Br_2 reactant for significantly less electricity than conventional water electrolysis[1]
- Clean water is co-produced with hydrogen and feedstock is reduced to a sterile ash residue[2]



1. HBr_{aq} electrolysis occurs between 0.6-1 Volt vs. water electrolysis at 1.6-2 Volts, thus there is a 40-70% reduction in required electricity per unit of hydrogen;
2. 4-6 kilograms of clean water is produced alongside each kilogram of hydrogen;

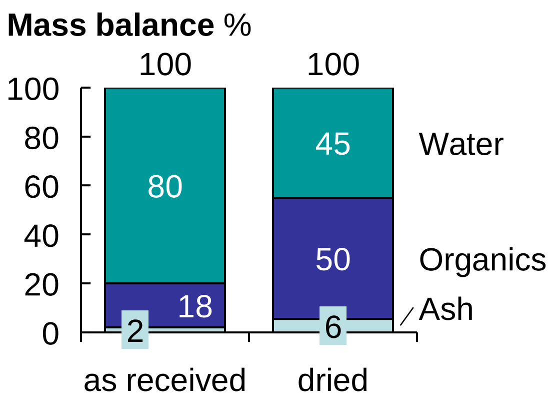
HyBrTec® chemistry basics

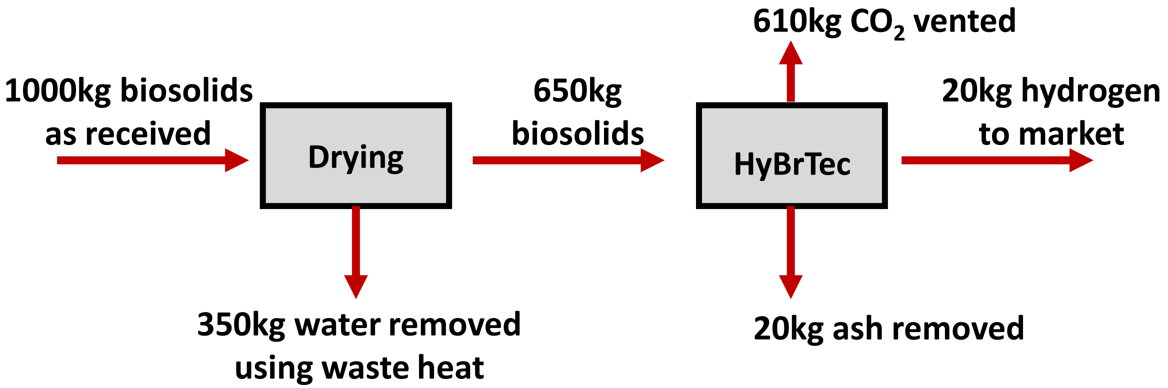
- Bromination[1]
  - Produces hydrogen bromide (HBr) from biosolids
  - Co-produces carbon dioxide (CO_2) & thermal energy (exothermic)
- Electrolysis
  - Dissociates hydrogen bromide (E_o = 0.555V) to regenerate bromine and produce hydrogen (endothermic)
  - HBr couple is easily reversible $2HBr \leftrightarrow H_2 + Br_2$ allowing efficient energy storage (in future applications)
- Energy available in product hydrogen
  - Reacting hydrogen with more energetic oxygen (E_o = 1.229V) allows a theoretical electric efficiency >100%[2]
- **What happens to contaminants?**
  - Pharmaceuticals, pathogens and organisms are broken down and killed
  - Sulfur and nitrates are converted into sulfates and nitrogen
  - Metals and other impurities form metal sulfates for sequestration or recycling
  - Remaining ash residue is sterile and safe for use as micro-nutrient fertilizer (or disposal)[3]
- Encourages a shift from fossil to local renewable resources
  - Scalable for any quantity and quality of feedstock exploiting locally available feedstock
  - high-rates & yields using compact, commercially available components

1. Bromination is analogous to combustion (burning) of wood (cellulose) with oxygen from air, only bromine is the oxidizer, consequently HBr is formed instead or H_2O.
2. Biowaste-to-hydrogen-to-energy has a theoretical efficiency of 212% by omitting the energy content of biowaste; however, if feedstock energy content is included, process efficiency is 67%.
3. The ash residue concentrates contaminants found in the source feedstock. If biosolids with cadmium, lead, arsenic, then this should be disposed. If animal manure, then can be used as fertilizer.

Mass balance explanation

- 1 wet tonne biosolids as received (80% water, 18% organics, 2% ash)
  - Dry to 45wt% water (45% water, 49.5% organics, 5.5% ash) by removing 350 kg water using reaction waste heat
  - React to produce 20kg hydrogen + 20kg ash + 610kg CO2
  - 350 kg of water available from drying biosolids and 50 kg of water from electro-osmotic transfer in electrolyzer[1]

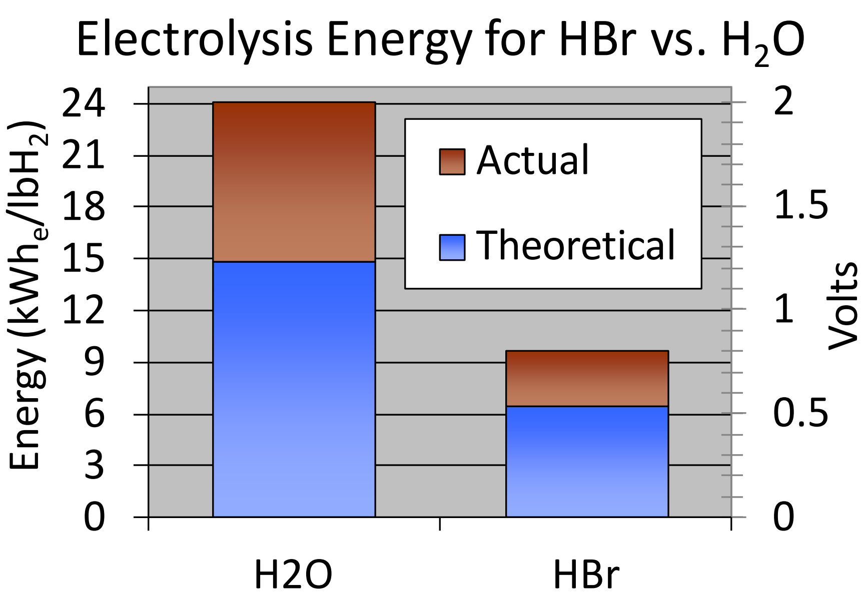


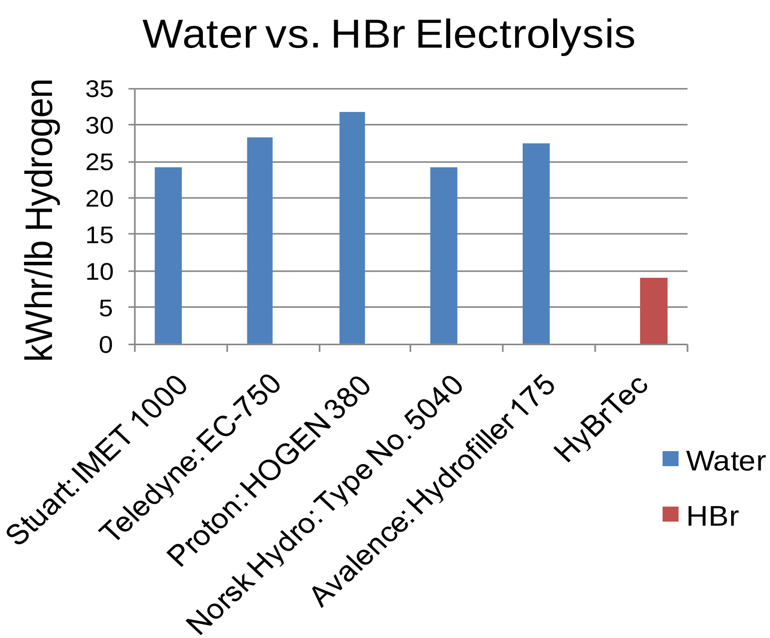


1. 2-3 molecules of H_2O are transferred with each proton across the electrolyzer PEM, resulting in pure water at anode

Hydrogen production via HBr electrolysis

- Re: hydrogen production: "… the hydrogen bromide (HBr) cycle looks the most promising because of its wider operating window (i.e., large current densities), lower cell voltage, less expensive catalyst (RuO_2 rather than Pt), and more stable operation."[1]
- **HBr electrolysis occurs at less than half the voltage (energy) of water electrolysis**
  - Below right shows actual energy requirements of commercial water electrolyzers[2]

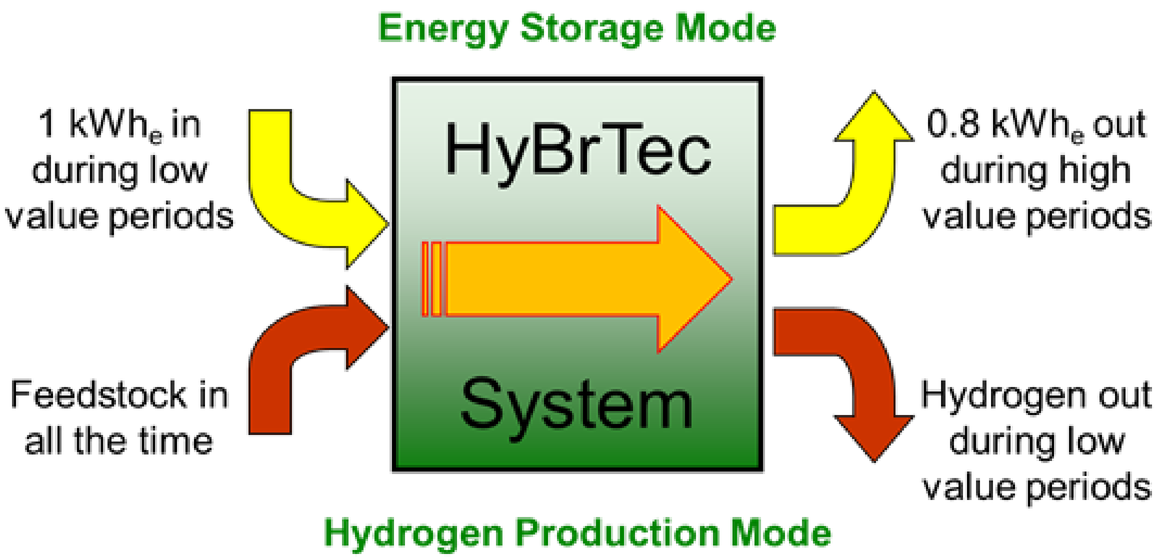




1. *IV.I.3 Low Temperature Electrolytic Hydrogen Production,* SRNL Contract #: DE-FC36-04GO14232, DOE Hydrogen Program, FY 2005 Progress Report;
2. *Summary of Electrolytic Hydrogen Production (Water Electrolysis)*, September 2004, NREL/MP-560-36734;

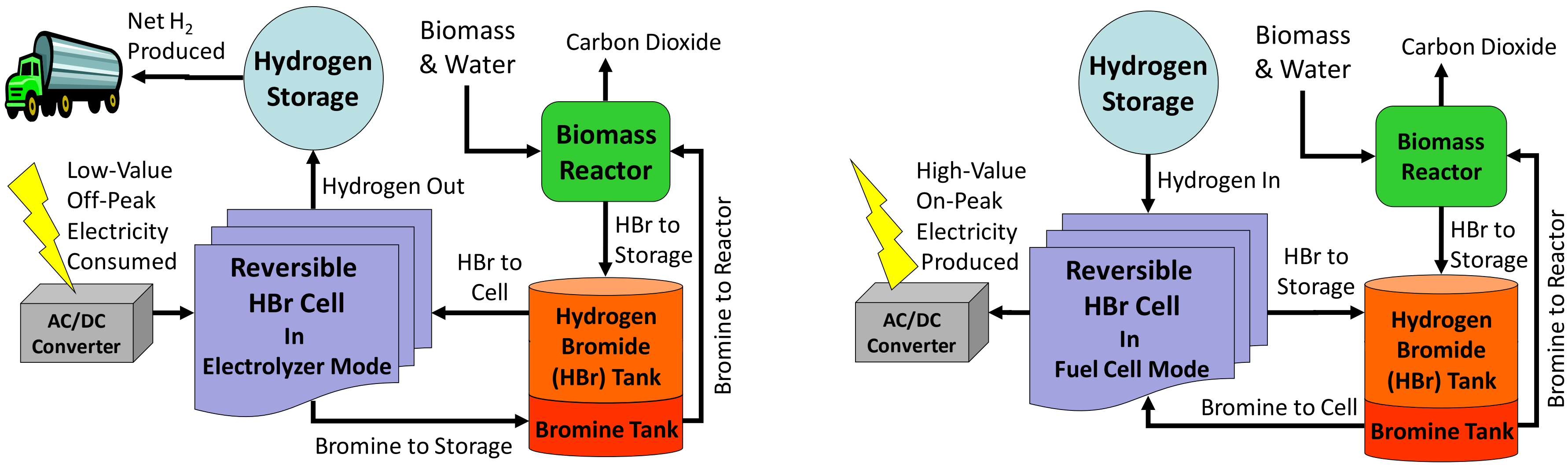
Energy storage "option"

- HBr electrochemistry is reversible ($2HBr \leftrightarrow H_2 + Br_2$)
  - **Charge**: electrolyze HBr into H_2 and Br_2 with electricity
  - **Discharge**: produce electricity by recombining H_2 and Br_2
- HyBrTec can be optimized for preferred amount of energy storage



Energy storage "option" explained

- HyBrTec® combined with HBr flow battery technology offers a triad opportunity to treat biosolids, produce hydrogen, and provide electrical energy storage
- System can switch between two modes to always operate, doing waste elimination 24-7 coupled with 8hr electric discharge during on-peak, and 6hr recharge plus 10hr net hydrogen production during off-peak to optimize asset utilization with the exact hours of each mode being fit for purpose



Recharge (H_2 Producing) Mode

Discharge (H_2 Consuming) Mode

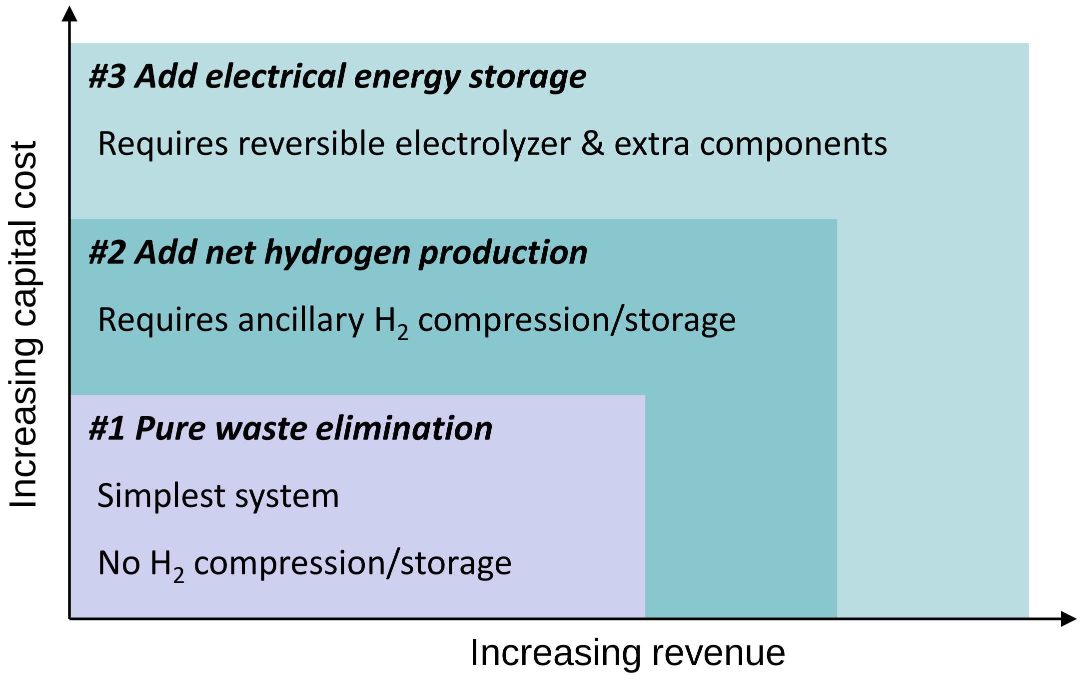
Current Status of HyBrTec pilot

- Pilot now being engineered & fabricated for demonstration
  - Initial design, specifications, and project plan complete
  - Detailed engineering and initial procurement now being undertaken
  - Fabrication of pilot expected to commence in November
  - Test & Evaluation to start in 2022

- Opportunity at example WWTP
  - ~300 wet ton/day biosolid production can yield ~6,000 kg/day hydrogen
    - Hydrogen used in transport will displace 12,000 gallon of diesel/day (45,000 ton CO_2/year)
  - WWTP uses 5-11 MW_e from grid and generates 2-3 MW_e from own biogas generators
    - Full HyBrTec system will add ~4 MW_e load to make its hydrogen
    - Hydrogen used to make electricity in 70% efficient fuel cell will produce 5.8 MW_e

Three HyBrTec Options explanation

- Three HyBrTec "options" depending on customer requirements and specific market conditions
  - 1. Pure biosolid/waste elimination in which product hydrogen is used to meet process electricity requirement
  - 2. Waste elimination with net hydrogen production when hydrogen market is more valuable than electricity
  - 3. Above with electrical energy storage added to do load leveling and provide back up power
- Each option adds cost, and market conditions need to balance these costs with additional revenue



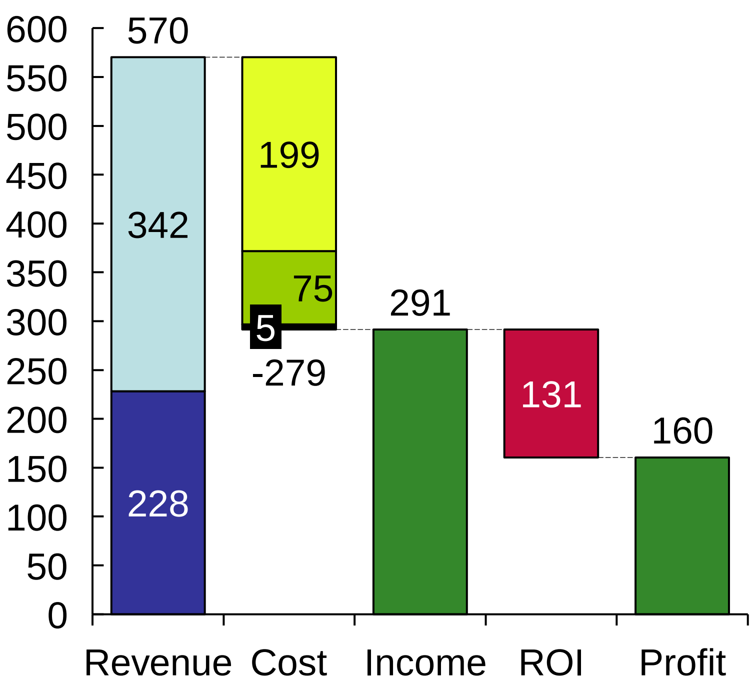
Process economics explained

- The ability to sell our systems is based on the initial acquisition cost, operating expenses, and revenue streams allowing a profitable facility:
  - Initial capital cost is impacted by system capacity (economy of capacity) and mass production efficiencies (economy of repetition)
  - Operating expense is based on the labor, maintenance, and electricity costs
  - Revenue is dependent on the biosolid tipping fee, the hydrogen sale price, cogenerated heat, and the value of CO_2 emission credits that may be monetized
- Federal & state incentives can reduce the initial acquisition cost and provide additional annual revenue
  - State & federal incentives, loan guarantees, cap & trade credits and subsidies are not included in the financial analysis, nor are the benefits of energy storage
- The following economics are based on our **Alpha product** which is marketed first to meet nascent hydrogen demand while solving part of most WWTPs biosolid disposal problem
- Larger **Beta & Gamma products** are offered upon sufficient process validation to benefit from better scale economies from handling more biosolids

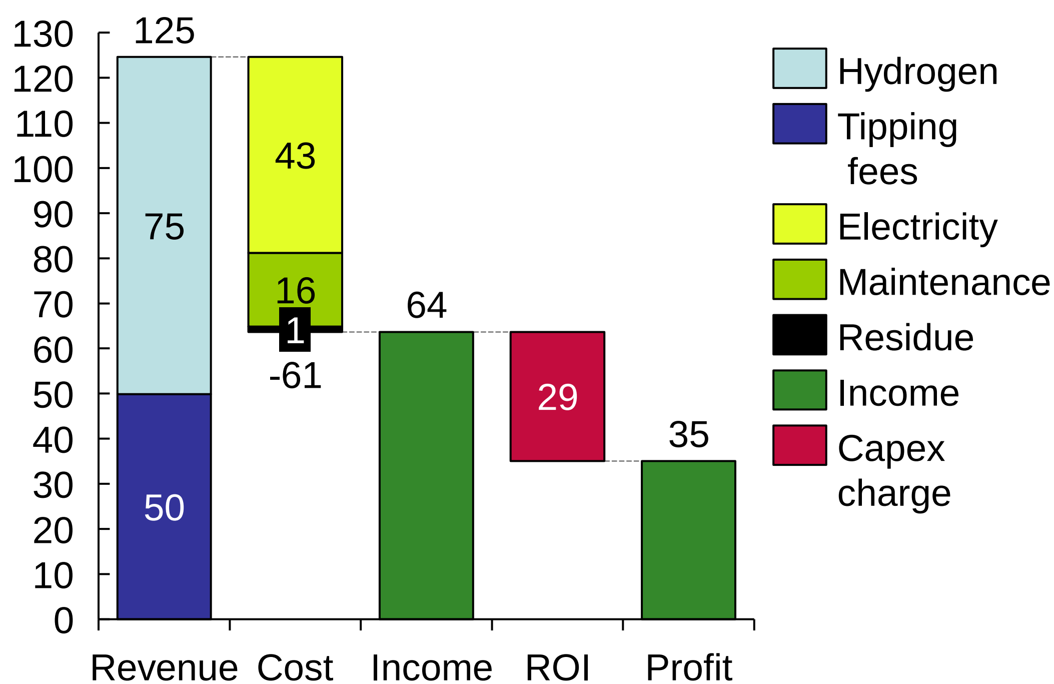
Alpha product – Revenue and cost waterfall[1]

- 13 wet ton biosolids/day to 330 kg H_2/day
  - 18% IRR based on $1.5 million purchase price (5.1 year payback)
  - Majority of revenue from hydrogen ($3/kg) and biosolid tipping fees ($50/wet ton)
  - 6% WACC for ROI, 7 cents/kWh electricity cost

Revenue-cost to treat biosolids
$ thousand per year



Profit from treating biosolids
$ per wet ton biosolids



1. Small Alpha system shown as an example though larger Beta or Gamma systems are economically favorable;

Market – Great opportunity beyond initial WWTPs[1]

- We address waste treatment/utilization and hydrogen production markets
  - Applicable wastes include: biosolids, municipal solid waste, manure, agricultural/food processing residuals, and plastics which are an economic and environmental burden to process and dispose
  - New green hydrogen is directed to fleet vehicles, buses and trucks, but can also serve the merchant market and chemical and refinery industries
- U.S. produces over 1 billion tons of wet-biomass annually
  - Can be converted to energy equivalent of ~55% of U.S. crude oil consumption
  - 220 million tons of this production requires $20-200 per ton to dispose[2]
- Biosolids are a particular problem
  - 80 million wet tons produced each year at disposal cost from $40-120 per ton
  - Costs rising 10%/year due to increasing concern over tightening regulations, oversubscribed landfills and resistance to land application
- Utilizing biosolids from domestic WWTPs with HyBrTec will require an $8 billion investment that will thereafter generate $2 billion in pre-tax profit a year for system owners

1. Waste Water Treatment Plants;
2. Other material is available for a fee as it must be collected and transported;

Conclusion

- Please get in contact to:
  - Share expertise in biosolid utilization,
  - Identify funding to support our work,
  - Find WWTP sites to host a demo together, and
  - Introduce partners interested in supporting our R&D

- Thank you for your time!
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