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Colorado Department
of Public Health
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Report Concerning Senate Joint Resolution 13-038

Concerning Measures to Increase the Percentage of Discarded Materials that are Beneficially Used Rather than Disposed of in Landfills

Prepared by the Colorado Department of Public Health & Environment

2014

Introduction

The waste management industry is continuously introducing new techniques and practices to improve how the solid waste we generate can be utilized in a more sustainable manner. This report will review the existing practices and emerging technologies being developed for beneficially managing discarded materials. Pursuant to Senate Joint Resolution 13-308, the waste diversion practices of recycling, composting and pyrolysis will be evaluated for understanding the potential impacts and roles they may have on increasing the economic and environmental sustainability of managing Colorado's waste-related resources.

Legislative Requirement

This report fulfills the requirements of Senate Joint Resolution 13-038 as follows:

1. The Colorado Department of Public Health and Environment will host a limited number of meetings with stakeholders to evaluate the use of recyclable materials that are beneficial for recycling, composting and pyrolysis; and

2. Develop a report with recommendations on how to further improve the economic and environmental sustainability of Colorado's waste-related resources, including collection, sorting, transportation, storage, return on investment, job creation, life cycle assessment, current markets, market development and subsidies.

Overview of the Sustainable Materials Management Hierarchy

A review of the management options identifying those that are most environmentally and economically advantageous is an essential starting point to a discussion of the transition from traditional, disposal-based solid waste management, to an approach of beneficially utilizing waste materials as a resource. In addition to the impacts that result from end-of-life management, the Sustainable Materials Management model developed by the United States Environmental Protection Agency assesses the overall impacts of a material throughout its life cycle. The concept of sustainable materials management incorporates a systematic review of each stage of a material's life cycle by identifying the actions that result in the most efficient use of a resource and minimize environmental impact throughout the life cycle of a product. Such actions reduce waste generation, while minimizing environmental impacts, conserving resources, preventing unnecessary energy use and improving economic value from improved efficiency.[1]

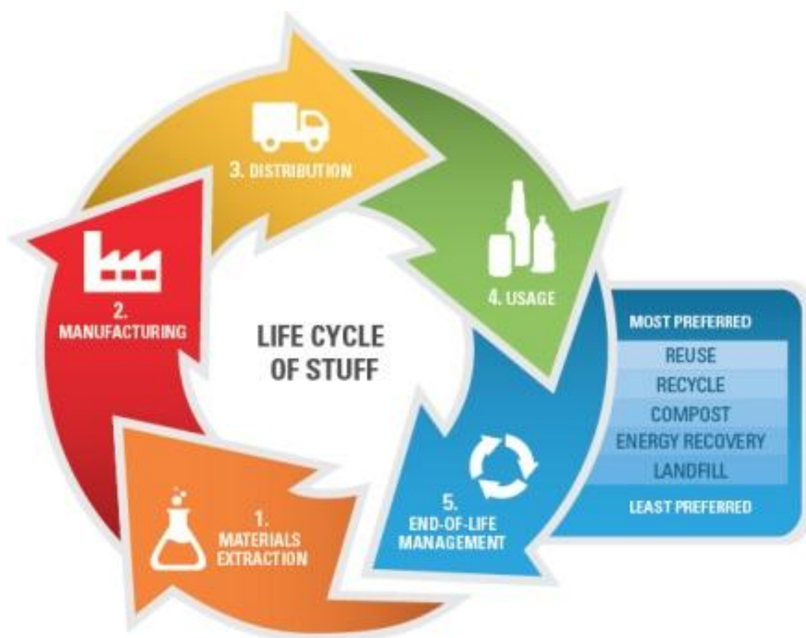


Figure 1. US EPA Materials Management Hierarchy, Climate Change and the Life Cycle of Stuff

The end-of-life stage in the sustainable materials management model includes a hierarchy that promotes the most advantageous means of utilizing a material in order to prevent materials from becoming waste and minimizing environmental impacts. While the most beneficial management method varies by material composition, a general hierarchy of preferred management practices was developed in accordance with the associated management and reuse benefits. The preferred management option is the direct reuse of materials without additional processing whenever possible. When a material can no longer be beneficially reused in its existing physical and chemical form, recycling though reprocessing into a new material and composting, are the preferred end-of-life management methods. Although recycling requires more energy and has a

[1] US EPA 2009 "Sustainable Materials Management, the Road Ahead" http://www.epa.gov/smm/vision.htm

larger environmental impact than reuse, remanufacturing of a material into a new product extends the life cycle of the material and avoids extraction and processing of virgin raw materials.

The materials extraction phase of a product's life cycle frequently accounts for the greatest energy and environmental impacts in the life cycle and can be avoided or minimized by recycling. In circumstances where no downstream markets for a material exist or the material cannot be recycled, the next preferred management method is to extract energy from the material. The end-of-life stage focused on energy recovery includes biochemical, thermochemical and physicochemical material conversion operations. The most notable conversion technologies include pyrolysis, gasification, anaerobic digestion and other means of extracting energy from discarded materials. The least beneficial option for end-of-life management of materials is disposal by landfilling. Beneficial energy extraction is still possible for materials that have been landfilled by operations that utilize a landfill gas recovery system.

Existing Waste Diversion Infrastructure in Colorado

While Colorado is often viewed as a leader in environmental issues, based on comments made during various stakeholder meetings, waste diversion operations frequently are lacking or remain undeveloped in many regions of the state and do not live up to the state's green image. Many work group stakeholders are surprised to learn that the Centennial State falls below the national average in the amount of material that is diverted annually from landfill disposal to recycling and composting. Although Colorado has made significant improvements in the amount of waste diverted in recent years, many gaps need to be addressed in order to boost the statewide diversion rate. Unlike most states, Colorado does not have a stated solid waste diversion goal.

Municipal Solid Waste Diversion Rates[2]

	2007	2008	2009	2010	2011	2012
Colorado	16.6%	19.6%	19.6%	20.3%	23.8%	26.1%
National Average	33.1%	33.2%	33.8%	34.1%	34.7%	34.5%

Even with the below-average diversion rates, it would be unwarranted to assume that the residents of Colorado do not want to recycle. Recent research in the 2012 Behavioral Risk Factor Surveillance System (BRFS) Survey by the Department shows the majority of Colorado residents make an effort to recycle. When asked *how often they recycled aluminum, plastic, paper and/or glass over the last year*, more than 80 percent of respondents claim to have recycled. Although the majority of Colorado residents surveyed statewide claim to recycle often, there was a noticeable divergence in the number of residents who recycle often in regions of the state where there is limited or no access to waste diversion facilities.

The limited access to waste diversion services and the lack of recycling infrastructure in many areas of the state is likely one of the main causes for Colorado's below-average waste diversion rate. Currently less than half of the counties in Colorado have residential curbside recycling services available. There are 145 registered recycling facilities within Colorado. However, only a few material recovery facilities with the ability to process and transport municipal solid waste recyclables to out of-state end markets are located outside of the Interstate 25 Front Range corridor.

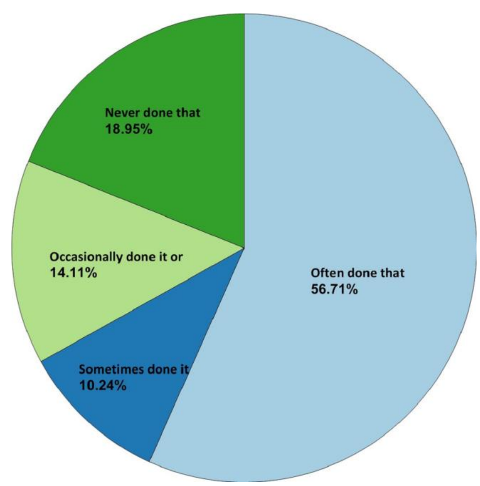
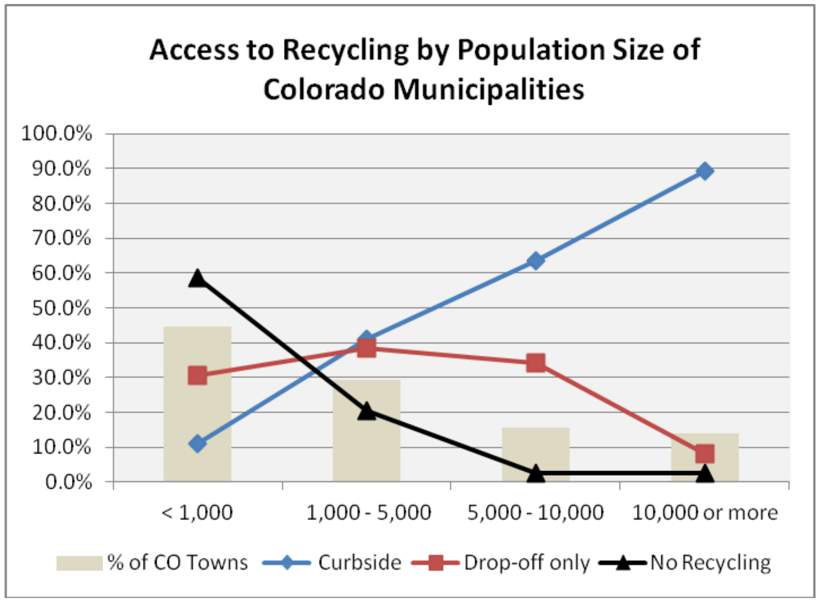


Figure 2. CDPHE's BRFS Survey results on how often Colorado residents have recycled within the year

[2] US EPA 2012 "Municipal Solid Waste in the United States, Facts and Figures" http://www.epa.gov/wastes/nonhaz/municipal/msw99.htm;
Colorado Department of Public Health and Environment 2013 "Colorado Solid Waste and Materials Management Program 2013 Annual Report to the Colorado General Assembly"

Similar to large scale recycling facilities, Colorado has a limited number of composting operations capable of accepting a wide range and large quantity of materials. Currently 30 composting facilities are operating in Colorado with only12 sites permitted to take food waste. The diversion of organic waste to compost is a challenge even for many urban areas. This is primarily due to operating and transportation costs for facilities that are often difficult to develop near residential areas. One of the most recent waste diversion developments in Colorado is the first anaerobic digestion facility located in Northern Colorado. The anaerobic digester facility, which will convert agricultural and organic municipal solid waste into renewable biogas, is planned to begin operations in 2014. The digester is projected to be the largest in North America.



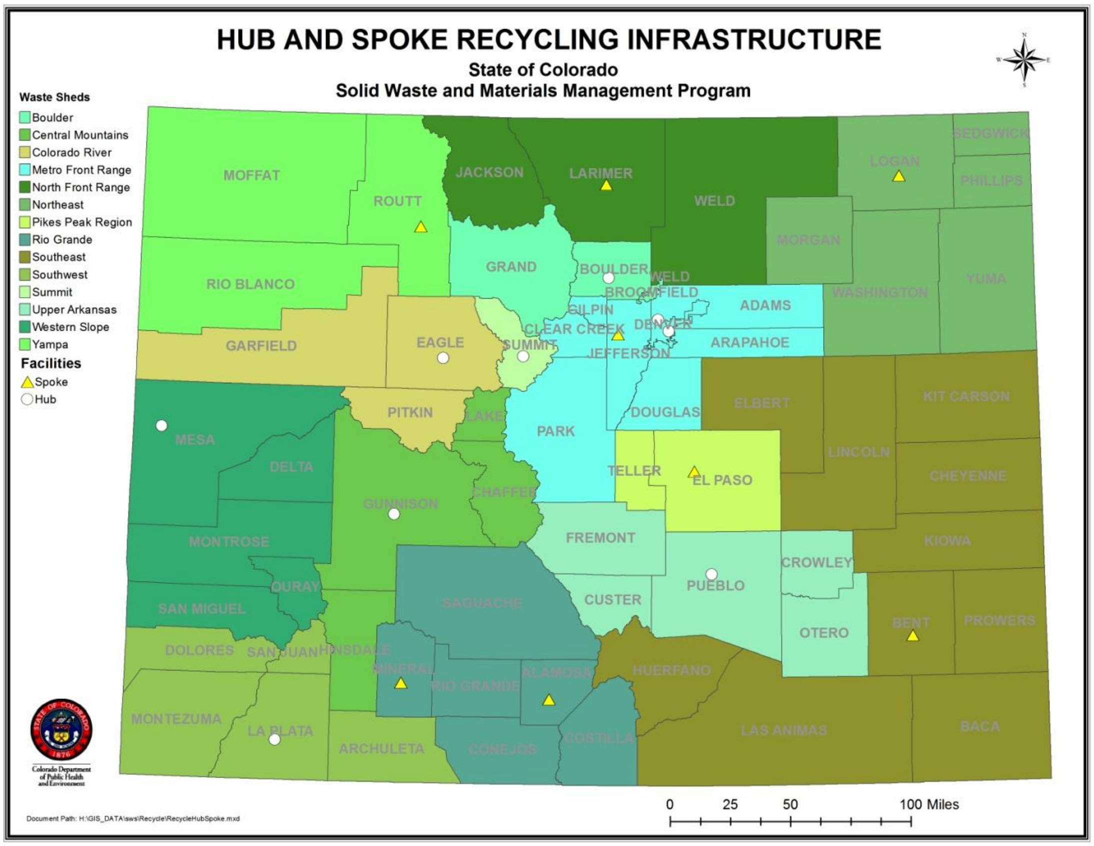
Currently, there are no Colorado waste-to-energy facilities that incinerate waste to produce energy. Waste conversion technologies including pyrolysis and gasification have been proposed. However, no facilities are currently permitted to use mixed municipal solid waste. Although there is no pyrolysis and gasification operations that utilize mixed solid waste as a feedstock, gasification operations for beetle-kill-derived wood byproducts currently are operating within the state. In addition, one pyrolysis facility is approved to use tire-derived product (tire chips) as a feedstock.

When comparing the existing infrastructure of waste diversion facilities across the state, there is a noticeable discrepancy between the urban regions and the surrounding rural areas. Many of the rural areas in Colorado have yet to establish the necessary infrastructure for waste diversion and rely primarily on landfilling waste. The rural areas of Colorado historically had less available recycling, composting and waste diversion infrastructure. Over the last few years with the recent development of the hub-and-spoke recycling model, there has been a notable improvement in recycling infrastructure for many of these areas.

Many communities have struggled to develop independent recycling programs because of the initial costs for recycling processing equipment and the difficulties of transporting low quantities of material generated by small populations in remote locations. The Pollution Prevention Advisory Board of the Colorado Department of Public Health and Environment has been promoting the hub-and-spoke model through the Recycling Resource Economic Opportunity Fund (RREO) grant to help rural communities develop access to sustainable waste diversion infrastructure. Hub-and-spoke recycling programs create economies of scale by developing regional partnerships for equipment, personnel, processing, transportation and material markets from multiple communities. Not only are equipment costs reduced, but long-haul transport of recyclables to market from remote areas is minimized. Rural communities struggle to generate enough recyclables to attract investments from large recyclers and cannot financially support a full-scale recycling program on their own. When multiple communities consolidate recyclables in a hub-and-spoke partnership, the increased quantity of recyclables collected is more likely to result in increased revenue potential that can offset operational costs.

Figure 3. The Four Corners Recycling Initiative provides recycling in Montezuma County using a hub and spoke model in partnership with the county landfill for baling recyclables.

Hub-and-spoke recycling is emerging as the most workable framework for communities to sustain recycling programs due in large part to Colorado's geographic layout and the large number of small rural towns. As shown on the map, hub-and-spoke programs often cover very large areas that have low population density. The South East and East Central Recycling (SEEC) was the first hub-and-spoke program established in Colorado. The SEEC was established in the early 1990s and continues to provide recycling drop-off centers to the entire southeast region of the state. New programs are emerging that utilize the same concept as SEEC's, comprised of a centralized processing center servicing a large area of drop-off recycling/collection locations. The operations such as Recycle Creede in Mineral County and Clean Valley Recycling in Otero County provide access to recycling in many locales where there was no previous recycling.



2012 Waste-shed Diversion Totals

Waste-shed	Diversion	Disposal	Generation	MSW Diversion
1 Metro Front Range/ Boulder	466,348	2,928,664	3,395,012	13.7%
2 North Front Range	216,470	1,315,413	1,531,883	14.1%
3 Northeast	961	76,395	77,356	1.2%
4 Southeast	987	40,896	41,883	2.4%
5 Pikes Peak Region	56,205	737,744	793,949	7.1%
6 Upper Arkansas	908	191,783	192,691	0.5%
7 Rio Grande	653	35,554	36,207	1.8%
8 Central Mountains	2,929	36,351	39,280	7.5%
9 Summit	7,586	27,005	34,591	21.9%
10 Yampa	10,476	86,496	96,972	10.8%
11 Colorado River	40,022	198,365	238,387	16.8%
12 Western Slope	24,259	225,711	249,970	9.7%
13 Southwest	12,579	88,715	101,294	12.4%

Tonnage of material diverted in many of the rural wastesheds, noted on the table, has a great deal of room for growth. As hub-and-spoke operations continue to expand to new cities and communities, diversion rates will continue to increase and help bolster the statewide diversion and recycling rates. As shown in the 2012 Waste-shed Diversion Tools table, there is wide variation in the tonnage of material diverted depending on the region of the state.

One of the largest recycling challenges facing Colorado is the transportation of materials over relatively large distances, coupled with the lack of recycling end-use markets within the region. Although there are commercial end-use markets in Colorado for glass, ferrous metals and certain grades of plastic, most recyclables collected are exported out of state for remanufacturing. Although transportation can be a significant strain on recycling program funding, it is by no means a reason to not recycle. Research by the Oregon Department of Environmental Quality documents the breakeven point of energy from transportation versus the energy savings from recycling specific material types.

Breakeven Point on Transportation of Recyclables per Ton[3]

Material	Production Savings (MM BTU / Ton)	Truck (miles)	Rail (miles)
Aluminum	177	121,000	457,000
Plastic (PET)	59	40,000	157,000
Steel	19	13,000	52,000
Newspaper	16	11,000	43,000
Cardboard (OCC)	12	9,000	33,000
Glass	1.9	1,300	5,100

The recycling industry is a well known job-producing sector due to the high labor demand involved with sorting and processing materials. The value-added benefit from recycling rather than disposing of waste can result in job growth within the waste diversion and remanufacturing industry and has the potential to generate new jobs for Coloradans as waste diversion continues to increase. For every 10,000 tons of solid waste generated, it is estimated that material recycling may create 10 material recovery facility jobs and an additional 25 remanufacturing positions, as compared to one landfill position.[4] While the direct economic impact of the recycling industry in Colorado is not yet known, preliminary research by the Colorado Energy Office estimated 8,800 jobs in the recycling, reuse and remanufacturing sector within the state.[5]

Pyrolysis for Energy

Pyrolysis differs significantly from conventional waste-to-energy conversion operations that produce electricity by incineration of the waste. Solid waste incineration requires oxygen and yields CO_2 and other emissions from incomplete combustion. Pyrolysis degrades materials in an oxygen starved, non-reactive environment usually at the temperature range of 700 degrees – 1500 degrees F and results in a mix of syngas, oils and solid byproducts. The thermochemical conversion of pyrolysis is most efficient with lower-moisture feedstocks and can potentially convert all carbon-based materials to energy sources.[6] Pyrolysis systems use a kiln or tubular chamber that is externally heated, often using the self-generated syngas as the heat source. Higher temperatures produce mostly gaseous byproducts, and lower temperatures produce more liquid pyrolysis oils. Pyrolysis of mixed-waste operations are designed primarily to produce electricity generated by steam turbines. A high-recovery steam turbine can have a thermal efficiency conversion of 92 percent.[7] Pyrolysis also can be used to produce fuels from material-specific sources such as plastics, tires or other high-energy materials.

In its most basic form, pyrolysis has been around for centuries in the original form of carbonizing biomass to create fuels. While the technique of pyrolysis to generate fuel is anything but new, modern techniques that break down materials to

[3] Allaway 2008. "Materials Management, Climate and Waste: Making the Connection" Oregon Department of Environmental Quality
[4]Institute for Local Self Reliance. 2002 "Recycling Means Business" www.ilsr.org/**recycling**-means-business/
[5] Roberts et al., 2009 "Careers for Colorado's New Energy Economy" State of Colorado, Governors' Energy Office
[6] Barrows 2011 "Briefing Paper: What are "Conversion Technologies" Oregon Department of Environmental Quality
[7] Funk et al., 2013 "Waste Not, Want Not Analyzing the Economic and Environmental Viability of Waste to Energy Technology for Site Specific Optimizations of Renewable Energy Options" The Joint Institute for Strategic Energy Analysis

produce chemicals and liquid fuels and to generate electricity have revitalized interest in more fully developing the potential of pyrolysis. Pyrolysis has developed into a tool for managing solid waste that results not only in the beneficial conversion of useable energy stored in the solid waste but also reduces waste volumes.

When considering pyrolysis for managing municipal solid waste, it is important to review what materials are, and are not, viable feedstocks that can be beneficially utilized for energy production. When undergoing the conversion process of pyrolysis, organic or carbon-based materials are most beneficial for energy production. Common waste materials that are most valuable to pyrolysis include paper, cardboard, plastic, tires, dried food waste, dried wood waste and other materials that are predominately carbon.[8] Other materials that are often included in the municipal waste stream such as aluminum, steel and glass do contain enough BTU content to benefit pyrolysis operations.

The use of municipal solid waste as a feedstock in pyrolysis is a relatively novel notion in North America and currently does not exist in a commercial operation in the states. Even though pyrolysis as a means to manage municipal solid waste has not yet developed on a commercial scale within the U.S., Japan and Germany have been successfully utilizing the technology for decades. Some of the pyrolysis facilities operating in Germany and Japan are processing more than 50,000 tons of waste per year for energy. Notably, Japan and Germany have a distinct incentive to employ pyrolysis and waste-to-energy facilities for the volume reduction benefits due to landfill space limitations.

Commercial Pyrolysis Facilities Operating with Municipal Solid Waste[9]

Facility	Location	First Year of Operation	Tons of MSW
Waste Gen	Germany	1988	154 / day
Mitsui	Japan (x6)	2000 / 2003	400 -140 / day
Takuma	Japan (x2)	2003	180 - 130 / day
Techtrade	Germany	2002	350 / day
Scarborough Power	United Kingdom	2008	20,000 / year

Commercial scale waste pyrolysis operations in the U.S. were first developed in the late 1970s and were unsuccessful using the then-available technology. Two of the prominent U.S. waste pyrolysis operations include the 1975 Monsanto facility built in Baltimore and the 1977 El Cajon facility with construction costs of $20.6 million and $14 million, respectively. After numerous attempts at sustainable operations and engineering redesigns, both facilities were closed due to continuous problems resulting from design and operational flaws.[10] Like all emerging technologies, pyrolysis has advanced significantly over the years compared to the original designs and operations. Although it was determined that the Monsanto Baltimore facility was economically unsustainable without special funding and EPA subsidies, the facility was able to demonstrate that pyrolysis of municipal solid waste was technically feasible.[11]

Although there are no commercial pyrolysis operations in the United States that manage municipal solid waste, research into developing pyrolysis operations continues with several pilot scale facilities. In 2012 the U.S. Environmental Protection Agency compiled an inventory of conversion technology facilities including pyrolysis pilot operations that exist or are currently under permit review within the U.S. Most of the pyrolysis facilities currently being developed within the U.S. are material-specific operations for high BTU value materials such as plastics or crumb rubber. Few mixed-waste pyrolysis operations are currently being proposed. At the time of the report, only one solid waste pilot scale pyrolysis facility, located in Riverside Calif., had been permitted for operation.

[8] Hackett et al., 2004 "Evaluation of Conversion Technology Process and Products" University of California"
[9] Department of Energy/EA-1862 2011 "White Paper Pyrolysis Overview Background" Appendix D: Pyrolysis/Gasification Technology Around the World
[10] Department of Energy/EA-1862 2011 "White Paper Pyrolysis Overview Background" Appendix D: Pyrolysis/Gasification Technology Around the World
[11] Dvirka et al., 1980 "Update on Baltimore Pyrolysis Demonstration" http://www.seas.columbia.edu/earth/wtert/sofos/nawtec/1980-National-Waste-Processing-Conference/1980-National-Waste-Processing-Conference-48.pdf

Pyrolysis Facilities in North America[12]

Vendor Name	Status	Feedstock	Location	Product
Agilyx	Commercial	Plastics	Oregon	Crude Oil
Intrinergy Coshoction	Commercial	Blends of crumb rubber, carpet fluff, wood chips, biomass	Ohio	Crude Oil
JBI	Commercial	Plastics	New York	Diesel Fuel
Climax Global Energy	Demo	Plastics	South Carolina	Crude Oil
International Environmental Solutions	Demo	MSW	California	Syngas
Vadxx	Pilot	Plastics, synthetic fibers, solvents, waste oil	Ohio	Crude Oil, Natural Gas
Agriplas	Demo	Agricultural film, food containers, low or no value plastics	Washington	Crude Oil
Green Power Inc	Demo	Plastics	Washington	Crude Oil
International Environmental Solutions	Permitted	MSW	California	Syngas
Oneida Tribe	Pilot	MSW	Wisconsin	Syngas

U.S. EPA State Practice for Emerging Waste Conversion Technologies 2012

Energy production from pyrolysis operations varies depending on the efficiency of the plant and the desired products for end use. Most pyrolysis facilities that utilize waste as a feedstock are designed for power generation. The commercial pyrolysis of waste facilities in Japan and Germany produce between 1.5 MW to 8.7 MW and utilize between 140 to 400 tons of solid waste per day.[13]

One of the most controversial topics of waste-to-energy and conversion technologies is the emissions generated by the facilities. This situation may be due in part to problems with emissions by some of the first pyrolysis operations and thinking that pyrolysis conversion technologies are similar to waste-to-energy incineration facilities. Emissions generated by pyrolysis operations are comparatively less than emissions from combustion/incineration facilities because thermochemical processes are conducted in oxygen-starved environments, resulting in a reduction of oxides and other emissions.[14] While pyrolysis operations do generate pre-treatment emissions of particulate matter (dust), aerosols, oxides of nitrogen, oxides of sulfur, dioxins, furans, hydrocarbon gases, multiple metals and carbon monoxide; the engineering and design of emissions control systems have improved significantly over the last 10 years and are no longer a barrier to developing pyrolysis operations.[15]

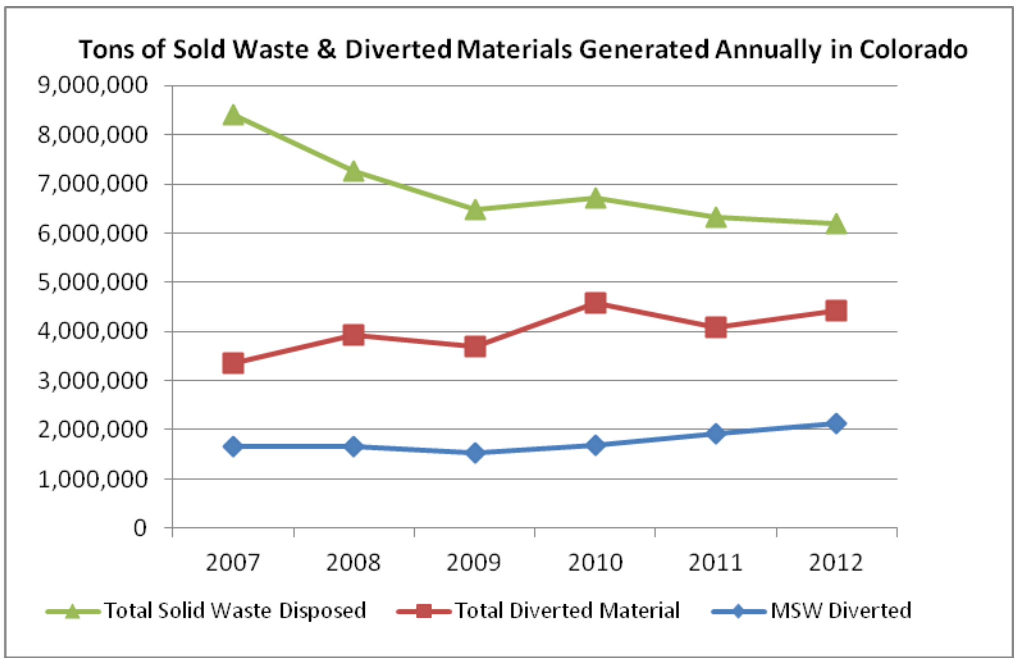
[12] EPA Office of Research and Development 2012 "State of Practice for Emerging Waste Conversion Technologies"
[13] Department of Energy/EA-1862 2011 "White Paper Pyrolysis Overview Background" Appendix D: Pyrolysis/Gasification Technology Around the World
[14] Youngs 2011 "Waste-to-Energy in California: Technology, Issues and Content" California Council on Science and Technology
[15] University of California Riverside 2009 "Evaluation of Emissions from Thermal Conversion Technologies Processing Municipal Solid Waste and Biomass"

Based upon research conducted by the University of California Riverside, analysis of emissions generated by pyrolysis facilities throughout the world indicate that sites currently operating with municipal waste feedstock meet each of their respective air quality emission limits. Additionally, most of the pyrolysis facility emissions meet all of the current emission regulatory limits of California, the United States, the European Union and Japan. In the case of dioxins/furans and mercury emissions, every process evaluated met the most stringent worldwide emission standards. Facilities with advanced environmental controls are very likely to meet regulatory requirements in California and subsequently in Colorado.

Pyrolysis in Colorado

Renewed and emerging interest in pyrolysis operations is due in part to Colorado's new renewable energy credits. Questions as to whether or not pyrolysis can be successfully implemented in Colorado's solid waste and materials management industry have yet to be answered and require analysis.

Due to Colorado's below-average waste diversion rates, it may be assumed that conversion technologies such as pyrolysis may have a suitable role to fill in Colorado's waste diversion industry to help improve diversion rates and the beneficial use of solid waste. While there are millions of tons of solid waste generated annually within the state, the amount of material that is disposed of in solid waste landfills continues to decrease with the growth and development of the recycling, composting and waste diversion industry. Colorado has experienced a 10 percent increase in municipal solid waste diversion over the last five years and is projected to continue on that trend. Although a fair amount of solid waste will remain undiverted even with the growth of the recycling and compositing industry, there are specific materials that may be highly sought after and in demand by both the remanufacturing end markets of the recycling sector and for energy recovery in pyrolysis.



Waste materials including plastics, paper, cardboard, wood waste and food waste are valuable commodities to the recycling and composting industries, as well as being valuable feedstock for pyrolysis. Locations that have pyrolysis-to-energy operations, or are planning to develop infrastructure to support pyrolysis, namely Germany, Japan and California, have waste management programs in place to ensure that high-value recyclable materials are diverted to pyrolysis operations only after recycling operations have removed materials. As mentioned in EPA's waste management hierarchy, reuse followed by recycling should always be the first actions of materials management with energy recovery only for non-recyclable materials.

Despite the fact that pyrolysis and recycling may occasionally be in competition for high-energy materials such as plastics and fiber products, there is a possibility that the diversion practices can work collaboratively and complement each other. The Los Angeles County Solid Waste Management Committee determined that pyrolysis to recover energy can work successfully even if the feedstock of waste utilized for pyrolysis is composed exclusively of the residual waste remaining after recyclable materials are source separated from a waste diversion processing center. Further, they indicated that combining recycling with pyrolysis of non-recyclable materials for energy recovery with marketable byproducts will increase diversion from landfills and enhance solid waste management and recycling programs.[16] The processing of non-recyclable waste plastics

[16] Predpal et al., 2005 "Conversion Technology Evaluation Report" The County of Los Angeles Department of Public Works

through pyrolysis has the potential to save the energy equivalent demand of 555 to 1,110 households annually, and about 16,500 to 27,500 tons of CO_2 emissions reduction per year.[17]

While some states are reviewing conversion technologies as the next step to enhance their waste diversion plans, Colorado has not established access to recycling in many parts of the state. Some concern exists regarding how the development of large-scale pyrolysis operations may impact areas where recycling infrastructure has not yet been developed and hub-and-spoke recycling infrastructure is in its infancy. In researching the impact pyrolysis and other conversion technologies would have on developing recycling infrastructure, state environmental programs had the following findings:

California Integrated Waste Management Board[18]

- Future recycling growth could be negatively impacted if recyclables were redirected to conversion technology facilities.
- Future recycling growth could be negatively impacted if waste streams that are currently untapped for recycling became unavailable to new recycling efforts in the future.
- Future recycling growth could be negatively impacted if local jurisdictions eliminated recycling and green waste collection programs and redirected mixed waste to conversion technology facilities.

Massachusetts Department of Environmental Protection[19]

- Pyrolysis and gasification may undermine recycling programs, because the plants' need for a steady waste stream with high fuel value may compete with recycling.
- Pyrolysis and gasification facilities are highly capital-intensive and thus require long-term investments (and often contracts), which may limit flexibility to adopt alternative waste management options or minimization strategies in the future. (MA DEP 2008)

Oregon Department of Environmental Quality[20]

- Recyclable materials could be diverted from recycling to conversation technology facilities, negating the significant environmental advantage of recycling that material.

The publicly available information on Colorado's two proposed pyrolysis operations indicates the facilities would be the largest pyrolysis-for-energy production facilities in the world. The Mitsui Babcock - R-21 facility located in Toyohashi, Japan is currently the largest pyrolysis municipal waste-to-energy facility, generates a continuous base load energy supply of 8.7 MW. The two proposed facilities in Colorado would produce a continuous base-load supply of energy of 15 MW. The proposed pyrolysis operations, raise questions as to whether rural communities would be able to generate enough solid waste to meet the demands of the pyrolysis operations.

Otero County, the planned location for one of the pyrolysis facilities, generated an annual average of 21,678 tons of solid waste per year for calendar years 2010 through 2012. The proposed pyrolysis operation requires between 240 to 300 tons of solid waste per day or 86,660 to 109,000 tons per year to operate. The facility proposes to operate seven days a week to generate base power. Because Otero County generates an average 59 tons per day, which is far less than the 240 tons per day required, the facility would be required to either import waste from out of county or would need to supplement the available solid waste with other materials such as waste tires. A similar deficiency arises in the location for the second proposed pyrolysis facility. Morgan County, which generated an average of 24,584 tons per year over the last three years would provide an average of only 67 tons of solid waste per day, providing 22 to 28 percent of the fuel needed to meet the demand of the proposed 240- to 300-tons-per-day waste pyrolysis facility. Additionally, it is important to consider that the reported landfill waste includes materials as concrete, soils, rock and glass, which are included in the reported annual waste generation totals and are not suitable waste streams for pyrolysis. These wastes would need to be removed, further reducing the tons of solid waste available as pyrolysis feedstock.

Waste tires remain one of the largest untapped resources in Colorado with over 60 million waste tires in storage and an additional five million waste tires generated every year. Waste tires have exceptionally high energy value, and may have an

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[17] EPA Office of Research and Development 2012 "State of Practice for Emerging Waste Conversion Technologies"
[18] California Integrated Waste Management Board 2007 "New and Emerging Conversion Technologies, Report to the Legislature"
[19] Tellus Institute 2008 "Assessment of Materials Management Options for the Solid Waste Master Plan Review" Massachusetts Department of Environmental Protection
[20] Barrows 2011 Briefing Paper: What are "Conversion Technologies" Oregon Department of Environmental Quality

important role to play with the pyrolysis waste-to-energy landscape. Pyrolysis can convert waste tires into a range of products including fuel, chemicals, electricity, and carbon char or black. The use of waste tires for energy production through pyrolysis is intriguing because tires have a BTU energy value 10 to 15 percent per pound greater than coal.[21]

Information on economic impacts created by waste pyrolysis facilities is limited due to the small number of operational sites. Research on employment opportunities created by pyrolysis operations compared to other waste management industries indicated that pyrolysis operations typically have automated operations that are managed through the facility's control room. Job creation as a result of material processing is expected to be minimal due to the use of mechanized waste processing and shredding operations.[22] Pyrolysis operations do have the potential for engineering and environmental management positions to monitor operational controls. Preliminary information provided by the proposed pyrolysis operation suggests that the 300-tons-per-day operations may employ between 40 to 60 positions per facility.

Stakeholder Perspectives

During the stakeholder meetings, the division evaluated the use of recyclable materials that are beneficial to recycling, composting and pyrolysis operations. Additionally the workgroup discussed best management practices in the context of environmental and economic benefits from the waste-diversion industry. A great deal of the conversation focused on information associated with the proposed pyrolysis operations. Throughout the stakeholder meeting process, multiple viewpoints were expressed both in favor of and opposed to integrating pyrolysis into Colorado's waste diversion portfolio. Some of the major discussion points and stakeholder comments expressed during the meetings are highlighted below:

<u>Benefits of Pyrolysis, Stakeholder Comments</u>

- Pyrolysis has potential to provide base load renewable energy.
- Pyrolysis can create new chemicals and fuels from waste that would otherwise be destined for disposal.
- Pyrolysis extends the life of landfills, diverting on average 85 percent of the solid waste generated and resulting in economic benefits to local governments.
- Pyrolysis can provide new end markets for waste tires.
- Pre-sorting at pyrolysis operations diverts certain recyclable materials and prevents household hazardous waste from entering landfills.
- Pyrolysis operations may create up to 60 new jobs per facility, which would be a significant economic benefit for rural communities.

<u>Concerns of Pyrolysis, Stakeholder Comments</u>

- Recyclable materials could be diverted to pyrolysis operations to meet feedstock requirements, trumping the environmental and economic benefits of recycling the materials.
- No operating municipal solid waste pyrolysis facilities exist in the United States, raising concerns whether the facilities would be able to meet emission control standards and potential impacts to human health and the environment.
- The high investment cost to construct pyrolysis operations has the potential to create ever-expanding feedstock demands and prevent the expansion of recycling and composting infrastructure in areas where it has yet to be developed.
- Converting non-renewable resources such as plastics for energy production by pyrolysis will have a negative impact on greenhouse gas emissions due to releasing bound carbon.

Life Cycle Analysis of Energy & Environmental Impacts

To fully understand the impact of materials and how end-of-life management practices can alter the environmental impacts of materials, it is vital to look at material management techniques through a life cycle analysis lens. Life cycle analysis (LCA) totals the energy use and environmental impacts generated throughout a product's existence from the natural resource extraction process, continuing through transportation, manufacturing, product use, and end-of-life management through reuse, recycling/composting, energy recovery or disposal. Environmental impacts reviewed in LCAs frequently focus on

[21] California Integrated Waste Management Board 2006 "Technology Evaluation and Economic Analysis of Waste Tire Pyrolysis, Gasification, and Liquefaction" University of California Riverside
[22] Tellus Institute 2008 "Assessment of Materials Management Options for the Solid Waste Master Plan Review" Massachusetts Department of Environmental Protection

environmental impact results including net energy use, greenhouse gas emissions/climate change potential, waste-produced acidification and associated ecosystem impacts.
A complete life cycle analysis of the various end-of-life management techniques is difficult to fully evaluate since there are no waste pyrolysis facilities operating in the U.S., and because LCA data is limited on mixed waste pyrolysis. The absence of operating pyrolysis facilities limits information and research available for LCAs. In 2009, a study was conducted to compile and analyze 20 different solid waste management LCAs in an attempt to see if any conclusions can be drawn from LCAs of different solid waste management options. Review of the LCAs, which were obtained from 11 peer-reviewed journals, resulted in all but one of the LCAs determining that the environmental impacts from recycling were less than that of all the other treatment methods. Further the study indicated that the thermal conversion of waste resulted in lower environmental impacts than landfilling, which aligns with the EPA's waste management hierarchy.[23]

The most comprehensive LCA literature review obtained was generated by the Tellus Institute, which included a review of over two dozen end-of-life management practices LCAs. Materials management options for the solid waste master plan of Massachusetts compares recycling, composing, and waste-to-energy, pyrolysis, and landfill disposal through the lens of an LCA with the findings summarized below:

- "From a life cycle environmental emissions and energy perspective, source reduction, recycling and composting are the most advantageous management options for all recyclable/compostable materials in the waste stream. This finding confirms the solid waste management hierarchy."
- From a life cycle net energy perspective, waste diversion through recycling provides the most benefit, saving an estimated 2,250 kWh per ton of solid waste. Of the other waste management technologies, pyrolysis facilities have the most potential for energy production at about 660 kWh per ton, followed by modern waste-to-energy incinerators at 585 kWh per ton, and then anaerobic digestion, and landfilling."[24]

To compare environmental impacts that result from end-of-life management practices, the Morris Environmental Benefits Calculator or (MEBCalc model) analyzes the results of each end-of-life management technique and resulting impacts. The table presents a summary of the life cycle emissions and environmental risks per ton of municipal solid waste generated as calculated using the MEBCalc model.

Morris Environmental Benefits Calculator Model:
Lifecycle Emissions per Ton of Solid Waste[25]

Management Method *	Pounds of Emissions (Reduction)/Increase Per Ton – Summary						
	Climate Change	Human Health - Particulates	Human Health - Toxics	Human Health- Carcinogens	Eutrophi-cation	Acidifi-cation	Ecosystem Toxicity
	(eCO_2)	(ePM2.5)	(eToluene)	(eBenzene)	(eN)	(eSO2)	(e2,4-D)
Recycle/ Compost	(3620)	(4.78)	(1587)	(0.7603)	(1.51)	(15.86)	(3.48)
Landfill	(504)	2.82	275	0.0001	0.10	2.38	0.21
WTE Incineration	(143)	(0.30)	68	0.0019	(0.01)	0.04	0.29
Gasification/ Pyrolysis	(204)	(0.36)	(1)	(0.0000)	(0.05)	(0.93)	0.09

Note: Modeling data for the (Morris Environmental Benefits) MEB Calc utilized 2006 MSW generation data from the State of Massachusetts for waste inputs.

[23] Cleary 2009 "Lifecycle Assessments of Municipal Solid Waste Management Systems: a Comparative Analysis of Selected Peer Reviewed Articles" Environment International 1256-66
[24] Tellus Institute 2008 "Assessment of Materials Management Options for the Solid Waste Master Plan Review" Massachusetts Department of Environmental Protection
[25] Tellus Institute 2008 "Assessment of Materials Management Options for the Solid Waste Master Plan Review" Massachusetts Department of Environmental Protection

As shown in the table below that assesses lifecycle energy savings per material management method, recycling reduces emissions and environmental impacts more than any other management option. Pyrolysis and gasification technologies included in this modeling exercise also reduce environmental impacts for most categories providing beneficial reductions of greenhouse gas emissions, particulate matter emissions, and other associated environments impacts as a waste management process.

Lifecycle Net Energy Generation Per Ton of MSW[26]

Management Method	Energy Potential (kWh per Ton of MSW)
Recycling	2,250
Pyrolysis	660
Waste to Energy Incineration	585
Anaerobic Digestion	250
Landfilling	105

From a life cycle net energy perspective, waste diversion through recycling provides the most beneficial management option per ton of solid waste saving an estimated 2,250 kWh per ton of MSW. For most materials, lifecycle energy savings from recycling are primarily a result of avoiding raw material extraction and mining virgin products. Pyrolysis of waste results in the second most advantageous option and has the highest energy generation benefit compared with the other energy recovery management practices.

Department Findings & Recommendations

Colorado has many options for reducing the current amount of waste disposed in landfills. Based on the sustainable materials management hierarchy, the most effective options to reduce waste in order of benefit include: 1) reducing waste generation, 2) increasing the amount of waste recycled and composted and 3) utilizing conversion technologies such as pyrolysis. Colorado also should explore the potential benefits of anaerobic digestion, which is beneficial for energy production and diversion of organic waste. Additionally, Colorado should continue to pursue developing local end markets for derived resources similar to the electronics recycling jobs act (SB 12-133), which has the potential to result in not only environmental benefits, but also economic growth and new employment opportunities. Colorado has the opportunity to develop new end markets for materials such as organics, tires, paint and other materials with currently limited recycling markets.

Although pyrolysis is feasible, it remains an unproven and unperfected technology in the U.S. for processing municipal solid waste into energy. Utilizing pyrolysis to manage unrecyclable materials, recycling facility residuals and other materials that do not have viable end markets may become the primary niche for energy recovery technologies. At this time, Colorado should continue to focus efforts on the current capital investments made through the Recycling Resources Economic Opportunity Fund's hub-and-spoke grants by continuing to develop diversion infrastructure through recycling and composting programs.

Additional information and research is required to effectively apply policies tailored specifically to Colorado's solid waste and materials management landscape. Developing a statewide waste reduction plan to identify and implement strategies emphasizing waste reduction, recycling, composting and energy recovery customized for each of the waste-shed regions across the state should be the next step to advancing sustainable materials management in Colorado.

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[26] Tellus Institute 2008 "Assessment of Materials Management Options for the Solid Waste Master Plan Review" Massachusetts Department of Environmental Protection