Thermodynamic Perspective on the Advantages of a Circular Plastic Waste Economy

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Joseph Brooklyn Bledsoe II

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

Signed: ____ Date ________________________
Joseph Brooklyn Bledsoe II

Approved: ____ Date ________________________
Kathryn A. Neeley, Associate Professor of STS, Department of Engineering and Society

Research Models and STS Framework

The current dominant system in which plastics are produced, utilized, and disposed of relies on large quantities of easily accessible resources, causes environmental degradation, and threatens competitiveness of countries (Di Maio 2015). The described system is known as a linear economic model and is clearly not a sustainable option for the future. The most defining characteristic that constitutes this model as linear and unsustainable is that the resources within the model are finite and steadily changing in quantity. Crude oil is a decreasing non-replenishable commodity and plastic products made from crude oil continue to accumulate as we mass produce them.

The popularized ideal, the circular economy (CE) model, provides a more robust alternative that may increase the longevity of our society that has become so heavily reliant on plastics. The key difference in this model is that resources are recirculated in a fashion that allows their quantities to remain relatively constant. "CE models maintain the added value of products for as long as possible and minimize waste, keeping the resources within the economy when products no longer serve their functions, so that materials can be used again and generate additional value." (Pearce and Turner, 1990)

The use of actor network theory (ANT) will help illuminate the underlying relationships that dictate the development and changes surrounding the plastic waste economy. ANT can be thought of as a framework for conveying the functions and entities related to a sociotechnical system. The semantically dense vocabulary provided by ANT will allow for concise expressions of the complex concepts proposed and will be drawn from Venturina (2010). The sociotechnical network that plastic waste is entangled is broad and complex, so for the purpose of this research, the systems described must be kept fairly abstract.

In addition to using ANT, the power of analogy will be used to help expose connections between abstracted technical concepts and contexts that are easily relatable. Far too often, technical information and argumentation is misinterpreted by readers simply by a disconnect in semantics and differences in personal understanding. For this reason, the underlying motivation for this research will be expressed extensively through analogies that can be understood by someone with little or no knowledge of the subject matter. Presenting concepts in this fashion will ensure that each reader receives the same understanding. “When human beings encounter something new, they often seek to grasp its meaning and relevance by identifying similarities with better known phenomena. This so-called analogical reasoning is generally understood as a cognitive process in which knowledge from one domain, the source, is mapped onto a target.” (Schwarz-Plaschg, 2018)

The structure of this document will begin by introducing enlightening thermodynamic concepts in a way that is easily relatable and digestible. After establishing a thermodynamic perspective, connections to waste management will be made to draw attention to its current inefficiencies. With a newfound understating of waste management, comparisons of the associated technologies will be analyzed to argue the push for reform towards a circular plastic waste economy. The novelty in this research lies in the connections made between thermodynamics and waste management as well as expanding the scale and timeframe of published literature to a more long-term global perspective.

Thermodynamic Analogies to Argue Intangible Concepts

To express the inefficacy of the current waste management system, it is helpful to abstract the network and analyze it in a thermodynamic sense. First, imagine what the purpose of a waste management system is. For the sake of this research, let it be assumed that the primary goal of waste management is to use the least amount of energy to remove waste from the environments we inhabit. With this definition of an ideal waste management operation, there is a clear and logical argument against our current system. The roots of this argument lie in the well-known and highly respected first and second laws of thermodynamics.

First Law of Thermodynamics & Importance of System Boundaries

"What goes in, must come out," is a typical expression used to describe the first law of thermodynamics which is technically defined to be that within a system boundary the mass and energy within that system must be conserved (Sandler 2017). This principle is crucial in understanding that *all* newly generated waste *must* go somewhere. It is a common mentality to ignore the final destination of the waste we produce as a consequence of our limited range of observation. No single person will ever be able to fully observe the entirety of this planet at once. Unfortunately, we are all limited to one set of eyes, ears, etc. and the sensory input we receive is as far as we can perceive the world around us.

Imagine someone who has never seen a landfill in person and has little to no interest in where their waste goes. For sake of simplicity, let's say that this person lives in a community in which all waste is transported to one single landfill. Relative to this person's perspective, they observe all of the waste they produce, fill an indoor trash bin. This trash bin then fills another larger trash bin outside of their home which is then emptied into a much larger trash bin on wheels best known as a “garbage truck”. This trash bin on wheels continues to collect the rest of the community’s waste, vanishes off into the distance, and isn’t seen again until next week when the cycle resets. From the perspective of this individual oblivious to landfills, there is no apparent problem because the immediate area around them stays free of trash. If their community were to be considered their system, then we would consider their system boundary to be the community’s city limits. From the limited view and knowledge of this individual, their waste management system displays no accumulation of waste. This yields a false observation of “steady state” which is defined as a time in-variant state of a system in which equilibrium is reached (Sandler 2017).

With this limited perspective, this individual will never recognize that 10 miles away from them, there is a hot, toxic, permanent mountain of trash that is growing in size at an exponential rate. This is the crucial importance of system boundaries. When considering the ideal community mentioned above to be the system, steady state is observed and there is no foreseeable problem. Although when the system boundary is expanded to their entire nation for example, there are several collections of accumulating waste that say otherwise.

Without any knowledge of this problem, this person will continue to dispose of whatever they feel the need to without any consideration of the repercussions. Unfortunately, the mentality of this oblivious person described is not too far from many of the individuals of the early 21st century. Contrary to this, are individuals who have had the accumulation of waste spill into their system boundary such as the residents of Northville, Michigan. The multitude of reports by these residents negatively affected by waste accumulation eventually led to the state of Michigan launching a lawsuit against the owner of the landfill, Arbor Hills (Forbes, 2020). Communities that were poorly placed next to this landfill were exposed to odors so offensive it inflicted nausea, headaches, and even sore throats in some cases. While it's unfortunate these people experienced such discomfort, it provides an excellent example of how ones' opinions and actions may be shifted so drastically due to a change in their system boundary.

Second Law of Thermodynamics & the Fight Against Entropy

Entropy is a quantity that measures the chaotic behavior or degree of order within a system. The second law of thermodynamics states that the internal generation of entropy of a system must be greater than or equal to zero (Sandler). This means that for a closed system, the entropy of said system may only increase or remain constant over time. Entropy in its purest sense can be thought of as a fundamental force of nature that drives change within a system. While the concept of entropy is typically first introduced in general chemistry as a "measure of randomness", its definition and impact are far broader than most realize. A more accurate description of entropy is that the arrangement of items within a discrete system converges to the most probabilistic state.

It's easiest to conceptualize this with the analogy of a ball pit. First imagine the installation of a brand-new ball pit at your local community center. Within this pit, there exist an equal number of red and blue plastic balls which are initially added one color at a time. Consider the shape of this ball pit's container to be a perfect cube. On the left side of the cube, all of the red balls are added and on the right side are all of the blue balls. The balls are placed carefully enough such that there is a perfect divide between colors and they form two sections of identical dimensions that contain only its respective color.

Consider this initial arrangement of balls to be in a state of zero entropy, meaning that the system is in its least probable arrangement. The balls are perfectly ordered and separated. It makes sense that they could exist this way because they were very carefully arranged into this orientation. Now consider how likely it is for the ball pit to remain in this orientation. If the ball pit were to remain untouched, it could stay in this arrangement for an indefinite amount of time. Now consider the addition of energy to this system. The first eager child jumps into the ball pit. The size of the child, the height of the jump, and the point of entry in the pit are all completely arbitrary and can be abstracted. Consider this initial jump, to simply be an input of energy. The energy this child is exerting on to this perfect ball pit system is immediately transferred and converted.

Some of this energy will dissipate as sound, small amounts of heat due to impact and friction, and most importantly for this example, kinetic energy of the balls. Kinetic energy is the energy of a body of matter which is observable by the velocity of the body and directly dependent on the mass of the body. The balls directly contacted by the child will move and exert a chain reaction in which all of the surrounding balls transfer energy to their adjacent neighbors until all of said energy has completely dissipated. After the dive, the child decides to remain perfectly still at the bottom of the pit for a couple minutes. Consider this child’s long pause to be the second state of the system. Comparing the initial state in which we defined the entropy to be zero and this second state, it’s recognized that the amount of energy in the child’s jump was greater than the energy of the resultant sound, heat, and other observable forms of measurable energy in the system. If this is the case, what happened to the rest of this child’s energy?

The answer is that it was converted to the entropy of the ball pit system. Carefully examining the orientation of balls in this second state, it's noticed that the once perfect divide of colors has now been interrupted. Some of the red balls have shifted into the blue ball section and vice versa. This change in arrangement is the essence of entropy and the total combination of this child-ball pit system's energy and entropy is the basis for "Gibbs Free Energy". The resultant relationships between energy, entropy, and free energy are the foundation of thermodynamics. This exchange between free energy, energy, and entropy is a critical consideration in the design of any chemical process. In the next section, it will be presented that our planets' waste management system is completely analogous to a chemical process design.

Connecting the Ball Pit's Entropy to Refrigeration

Refrigeration works by moving energy in a direction opposing the thermal gradient of the space being refrigerated and its surrounding environment. The natural flow of heat is a consequence of the second law of thermodynamics described above. Just as the balls in the ball pit naturally moved to a "mixed up" arrangement, the air molecules in a refrigerator tend to transfer their heat energy from hot to cold such that it gets "mixed up". The desired state of a refrigerator in which that divide between hot and cold molecules stays intact, is analogous to the divide in colors of the ball pit. The input of additional energy is required to keep the hotter gas molecules (red balls) outside of the refrigerator from transferring their energy to the colder molecules (blue balls) on the inside of the refrigerator. Keeping these hot and cold molecules from mixing, is analogous to if you were constantly reorganizing the colored balls of the children's ball pit to maintain that perfect divide. Now on top of that imagine your effort to organize the balls is represented by the addition of new red balls. So, as you're attempting to organize the red and blue balls, new red balls are appearing that you must toss out of the pit over time. The faster you're re-organizing, the more of the red balls you must throw out. As you could imagine, it would take a lot of effort and energy to keep those balls organized and this additional energy is of course what the power chord of a refrigerator is for.

With this analogy, it should be clear that a refrigerator doesn’t make heat go away, it merely removes it from the system boundary of the refrigerator. As heat from the surroundings invade the refrigerator, the energy supplied by the power chord is constantly removing the invading heat. It’s crucial to recognize that this is generating new heat in the process and the overall heat (number of red balls) is now greater than before.

Waste Management is a Refrigerator

Consider that the air conditioning in your home has just given out and it’s 100 degrees Fahrenheit outside. You have a couple options including opening the windows, doing nothing, or attempting to cool yourself with your refrigerator. You may be tempted to pick the latter option and attempt to cool your sweltering house down with your still functioning home appliances. You may be enticed to naively open the doors of your refrigerator and stand in front of it accepting some fresh cool air. This may cool down your body when you initially open the door, but the second law of thermodynamics and the concept of refrigeration suggests this wouldn’t work for long. Just as described before, refrigeration is constantly generating heat in attempt to re-organize the hot and cold molecules. This translates to the local area surrounding your body getting cooler, but overall, your 100-degree house is now getting hotter.

This story of fixing a hot house is no different than the story of our current linear plastic waste economy. Just as the problem of excess heat in the local area of your body is mitigated, we are only mitigating the excess waste in our local communities. Just as the overall temperature of the house is rising, the overall amount of waste on our planet is rising. The thermodynamics are analogous and clearly reveal that the energy we are putting into the waste management network merely mitigate entropy in our local system boundaries and do not address the problems of our overall system.

Now imagine the clever idea of putting the backside of your refrigerator outside of your window with the cool side still on the inside of your window. You have now successfully made your house cooler by creating a very cumbersome window air conditioning unit. This works because you have changed the system boundary of your refrigerator appliance. Now the heat from inside your house is being pulled through the cold side and exits out of the hot side exterior to your house. The inside of your house is now essentially the inside of a refrigerator and the energy supplied to the refrigerator is directing all invading and newly generated heat outside of the house. This is putting your addition of energy to better use by shifting the system boundary. Instead of just quickly and immediately cooling the area around your body with the door wide open, you are slowly but steadily cooling the entire house. This is the fundamental advantage of a circular plastic waste economy. While the alternative methods involved such as recycling and bioplastics have an upfront cost that is higher than producing virgin petroleum-based plastics. They are a net positive when considering our problem from a global system boundary on a long-term basis.

Tying Analogies to Reality Yields Fresh Perspective on Existing Research

In both the hypothetical and real scenarios, there will reach a point in time when the habitable area becomes inhabitable. If humans are to continue thriving on this planet, we must construct a clever way to redirect our waste management's energy input just as it was accomplished in the refrigerator analogy. The first step in achieving this is recognizing our system boundary of interest must be global and cannot be considered just at the level of our local communities. This means that a clean city doesn't necessarily mean a clean planet, which in turn means progress toward the primary goal of waste management isn't necessarily being achieved, even if it seems to be from our limited perspective.

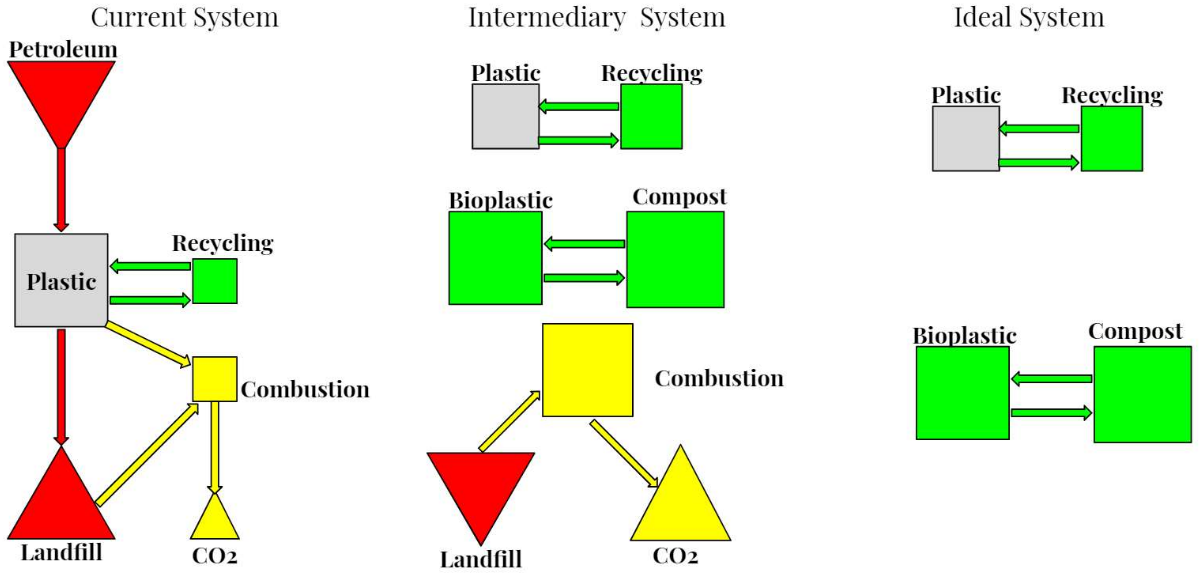
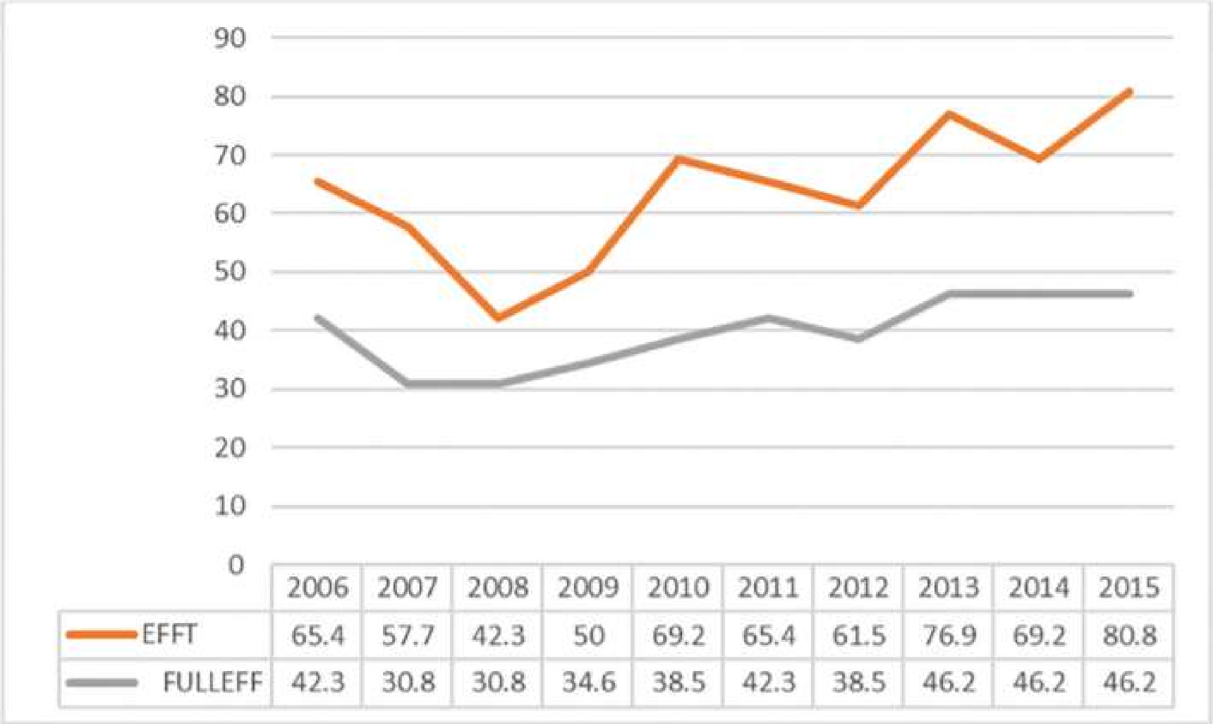


Figure 1. Current and Future Plastic Production Lifecycles: A broad generalization of the current life cycle of plastics today including the strong reliance on petroleum for plastic, landfill accumulation, and proposed life cycles to rely more heavily on biodegradable plastics and recycling. (Bledsoe, 2020)

Each object in Figure 1 is a fundamental actor of the plastic lifecycle and their size roughly compares their relative quantities. Cube shape actors represent a quasi-steady-state in which their associated quantities may fluctuate, increase, or decrease over time, but remain constant relative to neighboring actors. The triangles represent accumulation meaning that the quantity relative to other actors is not constant. Moreover, upward and downward triangles indicate an increasing or decreasing rate of change respectively. Green, yellow, and red are used to indicate the net environmental impact associated with each actor as sustainable, semi-sustainable, or unsustainable. Each of these presented actors may then be defined as subsystems in which the social behavior, technological implications, and political aspects influencing them can be considered independently.



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
EFFT	65.4	57.7	42.3	50	69.2	65.4	61.5	76.9	69.2	80.8
FULLEFF	42.3	30.8	30.8	34.6	38.5	42.3	38.5	46.2	46.2	46.2

Figure 2. EFFT and FULEFFF Yearly Evolution (%): Signifies the progress in intermediary life cycle transitions for European nations (Adapted by Joe Bledsoe from Robaina et al., 2020)

Achieving a global circular economy will require a series of transitional periods. The three systems laid out in Figure 1 will likely take decades to transition between and the progress of each transition will vary for different areas of the world. Figure 2 showcases multiple nations' cumulative progression towards an intermediary plastic lifecycle over the course of one decade. The metrics used, EFFT and FULEFFF, represent nations that are efficient or fully efficient and nations that have Multidirectional Efficiency Analysis (MEA) scores equal to 1 for that year. While it is apparent that these countries are shifting steadily to a CE, their progress fluctuates and is a consequence of many underlying factors that can be broadly described by the network in Figure 1. Moreover, this visualization is only representative of highly developed European nations and data encapsulating global progression towards a CE is too broad to capture. For this reason, it is best to underestimate reported CE progression and analyze waste data independently.

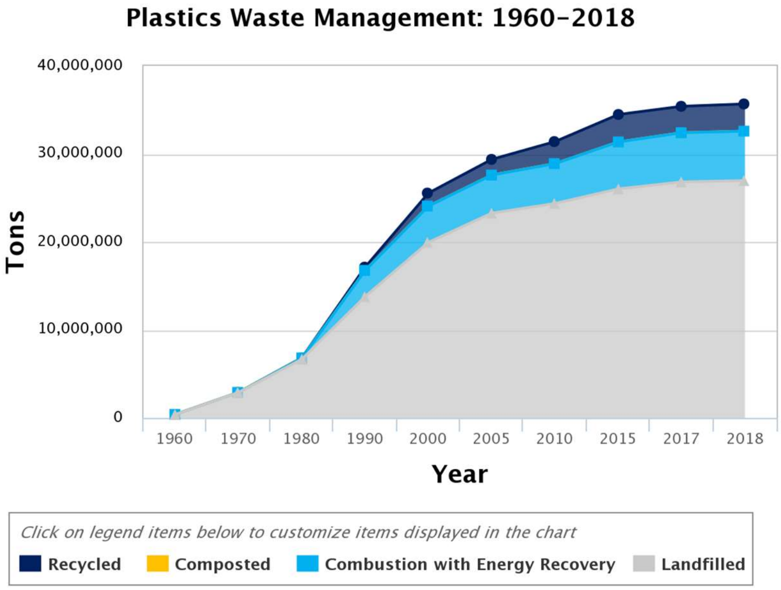


Figure 3. United States Waste Accumulation: Displays the trends of landfill accumulation and current alternative waste disposal technologies. (EPA, 2020)

Starting with the most obvious observation in Fig.3, the rate of plastic waste accumulation is rising. Not only are landfills increasing in size, but the volume of plastic they gain each day is increasing as well. This does not come as a surprise considering that the global population is steadily increasing and the waste generation per capita is also increasing (EPA 2018). This alarming increase in the United States counteracts the progress seen in the European nations of Figure 2 and is at the root of this paper's argument. Even though efforts to halt the accumulation of waste through alternative methods are growing, they are not being applied to the correct system boundary. The total mass of material recycled and combusted is growing each year, but it is still clearly not enough to reverse the current rate of waste accumulation. If society desires to slow contributions to pollution, it is paramount that waste management carefully directs its energy use to the most thermodynamically favorable methods with respect to a global boundary.

Conclusion

To better understand the behavior of Figure 2 and develop tangible plans for the transitions portrayed in Figure 1, each of the fundamental actors have already been extensively researched by several of the mentioned authors. Instead of reporting the already available findings from this research, an alternative approach has been taken to stress the importance of and elaborate the motivation for the transitions to a CE rather than the specifics of the transitions themselves. This approach seemed appropriate considering that the facts surrounding this topic are easily accessible and have already been published in a concise and factual manner. The existing works of Antelevia 2019, Robaina et al. 2020, and Di Maio et al. 2015 make it very clear that bioplastics in conjunction with recycling are the most logical solution to a true CE. The specific economic disadvantages of bioplastic and recycling technologies can be found in Camila et al. 2020, Niaounakis 2013, and Yadav 2020. Rather than re-iterate these already published findings, I have attempted to share the vast and complex understanding of dynamic systems I have accrued throughout my undergraduate education. I believe perspective and conceptual understanding are an undervalued asset and hope that the analogies I have provided may inspire new beliefs in the importance of waste management reform.

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