A Thermodynamic Analysis of Development Technologies

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Introduction

Where will technology go? What can technology do? These questions lie at the center of one set of debates with regards to the direction of technology development, policies on resources and technologies, their need and utilization and the social, political and environmental impact of these choices. These include current and emerging technologies that may impact energy (nuclear fission based energy and biofuels), waste management, food production, transportation, etc. They also include future technologies such as nuclear fusion.

One school of thought (pointing to the environmental impact of the rapidly growing fossil-fuel energy based economy) argues that we must take responsibility for the impact of our decisions. Another group argues that the cost of not using these resources or using alternative processes is too high, and speculates that technologies developed in future – fusion, perhaps – will resolve these questions. One response to such a thought process argues that policies cannot be based on miracles and uses heuristics to point out why such technologies may or may not be feasible given the history of technology development – but that is also speculation.

Such discussions have taken place around the question of waste management - primarily in urban settings. Waste to energy was a dominant technical philosophy that received much support (and continues to in the southern hemisphere despite much opposition). Technologists, urban planners, health experts and social experts have all weighed in on this topic. In the last decade, most of that discussion (and development) had been laid to rest in the US, Europe and Japan owing to the generation of highly toxic chemicals (dioxins) and a plethora of other pollutants. However, it is a discussion that is opening up again with a new set of technologies being presented.

Another large discussion that impacts energy policy significantly is brewing around the policies of bio-based energy. One set of researchers and policymakers argue that such a process may not be economically feasible. Another school argues that this strategy is bound to fail based on the amount of land necessary to develop this energy. On the other hand, other researchers claim that bio-based energy can be generated using mainly waste land (based on current use patterns) and using the right kinds of cropping cycles. Another set points out that such a technology has the potential for zero carbon emission into the atmosphere. Yet another group argues that appropriate technologies for bio-based refining could use the ‘waste streams’ from the process to develop chemicals (just like the petrochemical industry) leading to renewable (and hence green) energy and materials policies. These claims are countered by the first groups by pointing to the absence of efficiency, for example. The latter groups argue back by showing that petrochemical industry needed billions of dollars to develop its efficiencies. Into these discussions, another group of researchers with expertise in sociology and political science jump in with their comments on the impact of changing cropping cycles, effect of cash crops on small farmers, geo-political impact of lower dependence on petro-based energy, among others.

These are few examples of discussions and policy direction on issues of how people (and nations) solve pressing problems around energy use, waste management, water, agriculture, etc. There are a variety of perspectives around each of these issues, each quite informed in its own right and each rising from a superimposition of technology, economics, sociology, political science, among others. How can we really address the technologies that are being presented to resolve these problems when there are complex nuances that even technical experts and social and political scientists do not quite understand?

The scenario gets even murkier when we recognize that there is much as stake – not only from the perspective of people, of the future of our communities and our nations but also from the perspective of economics. Billion dollar profits are often riding on the direction of these policies and it is naïve to think that they do not influence research directions and policies. So this is not a simple objective technical analysis.

Often conclusions are based on assumptions which are often not explicitly stated and are speculative. They are driven by politics and economics, not necessarily by science or data. There was no sudden learning that led to the slashing of the budgets of National Renewable Energy Labs nor were there any new findings that led to allocation of large funds to this institution. Similarly, the claim by the UK government that nuclear energy will be the next wave of clean, sustainable energy was politically driven. In fact, a court in UK pointed out that the process to arrive at this conclusion was neither transparent nor did it take all perspectives into account and must be re-initiated. Public speculation has often been the façade for such policy moves.

Given these different influences, are there tools that can better help understand the feasibility and impact of technologies and hence direct the trajectory of policies? Which technologies and what policies are truly sustainable?

Methods of Analysis

The first real set of analytical tools that allow us to understand these technologies and the derived policies are based on data and on trends. These trends, however, cannot be taken at face value and must be understood in the context of their assumptions and the conclusions they present. The model or idealized systems developed to study these issues either simplified or are designed for a specific purpose or to prove a point.

We have already spoken of studies about crop yield and bio-fuel production. These studies pointing in opposite directions often make implicit assumptions that must be ferreted. How does this model study truly compare with current realities of petro-based energy? Will an economy of scale make bio-fuel more feasible compared to the model study? Can it be more decentralized and hence more accessible? Has the study accounted for cost of chemical-based inputs? What is the value of chemicals derived from the effluents? What is the efficiency? While the data is generated within a model system and with specific assumptions, it is interpreted more broadly (in the absence of any other choice) to make policy decisions. Policies that result are significantly defined by the background of the policy makers and their leanings. Thus, in a certain political climate, energy policies based on bio-fuels become feasible; in another climate (based on the same data) they might become unfeasible.

Similarly, studies on nuclear energy show different aspects of generation, and distribution. One set of data shows that nuclear energy can be a clean fuel without issues of global warming and environmental pollution. On the other hand, residents of Chernobyl will disagree. At the same time, proponents will argue that reactors and the technology have become more robust and reliable. Opponents will however argue that we have not begun to look at the radioactive waste (and its treatment) from decommissioning of nuclear reactors[i] and that will be significant. In addition, others have also pointed out that we truly do not know given the layers of secrecy surrounding most nuclear installations and their operations and do not really know how safe they are. Opponents will also argue that Uranium is not a finite resource either and under current consumption rates at 3.5 million tons will last 50 years[ii]. This analysis also estimates that if all of today's energy needs (15,000 terawatt-hours) were met through nuclear energy, our nuclear fuel would last between 3 and 4 years. Proponents will argue that energy from other fuels like Thorium are becoming feasible thus making this technology more viable. Again, from the cost perspective, analysts have argued the cost of nuclear based energy does not compare feasibly to fossil-fuel based[iii]. Past investigative reports show that British nuclear energy producers (private corporations) may have been subsidized by tax payers[iv] to keep the product competitive. Yet again, nuclear energy proponents have different counter-arguments. First – that the cost of cleaner energy has to be borne by society. Second – that economy of scale would make a difference. Third – the ineffectiveness of an institution cannot be held against the feasibility of a technology. These divergent conclusions are correct within the context of their studies. So how do we decide?

It is important to reiterate that all of these studies (and they are the best that can be done) were within narrow premises and smaller scopes. But when these conclusions are extended outside their scope to define broader policies, there are significant errors with grave impact. And yet, what other option do we have?

One option that presents itself as a way of analyzing technologies and their feasibility is to recourse to thermodynamics. Specifically, we could apply a law – such as the first and second laws of thermodynamics – to ask what technologies (or aspects of technologies) are feasible and what are not.

For example, if someone proposed a perpetual motion machine, she would have to present quite clearly how the device managed to achieve this – either by describing the mechanics of the device or by showing data of how the device works. During this show-and-tell, perhaps a keen critic might point out how it is not truly perpetual motion. Another innovator would then appear with another idea of a perpetual machine and so on. In reality we saw this phenomenon in the 1600s to 1800s. And this would have carried on (with immense waste of time and money) if it were not for the second law of thermodynamics proving that perpetual motions are impossible. Based on this law, we do not need large data sets to analyze every new perpetual motion machine – we know it is unfeasible[v].

Similarly, one could use the first and second law of thermodynamics to broadly ascertain the feasibility of current, emergent or future technologies. If one of these technologies implied that energy was being generated or destroyed, then clearly, the first law of thermodynamics is violated and the contradiction points to something wrong with the technology. If the conclusions of the proposed technology violated the second law of thermodynamics, the technology would be unfeasible and one could be sure that assumptions were being ignored or hidden in presenting the data. If the technology was consistent with the principles, the technology MIGHT be feasible.

The elegance of such a strategy is that we can apply established laws of thermodynamics to understand the scope and / or limits of technology. Specifically, thermodynamics is the science of feasible materials and energy states in a system under different conditions as well as changes in the materials and energy states during any well defined process. Different areas within this subject attempt to understand these processes for bulk matter and at the molecular level, for applications in chemical systems, mechanical systems, electro-magnetic systems and nuclear systems. Thermodynamics can predict non-feasibility of certain material or energy states or of conditions telling us what is impossible.

In this analysis, we use thermodynamics to understand whether a particular technology is truly sustainable – how does it impact the quality of energy and materials of the system within which it resides? This paper is meant not just for engineers and scientists familiar with thermodynamics –simple derivations that most engineers and scientists would consider trivial are provided as appendices.

The Laws of Thermodynamics

Thermodynamics is the knowledge of a material and of the possible processes of change of that material under different conditions. One can know a material by understanding the components of the material, their relationship to each other and the energy of the material. By understanding what relationships between the components of the material and the energy are feasible and what are not, one can predict feasible material structures and possible processes of change of that material. When one understands these processes, one also learns about flow of energy or work done during these processes. Two key parameters are the energy and the entropy of the material or the system of materials. During processes of change, we are interested in the changes in energy and in entropy of the system and how they move between different materials or different components in the system.

The first law of thermodynamics says that energy cannot be created or destroyed. That law says that energy in one form can become energy in another form, and that energy disappearing from one form will appear in another – but the total energy will be conserved. But it does not tell us which transformations of energy are possible and which ones are not. For example, the first law can tell us that 10 joules of energy in a metal can be moved to 10 joules of energy in water. However, we have noticed that 10 joules of energy will only move from a hot metal to cold water. Spontaneously (or by itself), 10 joules of energy cannot be transferred from ice cold metal vessel to hot water poured into it. We know of no real example where (by themselves), hot water in touch with cold container will become hotter by 10 joules of energy while the cold metal vessel becomes cooler by 10 joules. In fact, we know that spontaneous transfer of energy will happen from the hot water to the cold vessel. From the perspective of the hot water, the energy in the cold vessel is useless – the hot water cannot use it. From the perspective of the vessel, the energy in the hot water is useful – it can use it to become warmer. The second law of thermodynamics talks about usefulness of energy and materials.

In ordinary English, it says that when left to itself or without any external influence (energy or work) the energy or material content of a system cannot become more useful. It will either stay at the same in level of usefulness or become less useful. Described simply, entropy is a measure of ‘usefulness’ of energy or material. ‘Useless’ or ‘useful’ as defined in this text is not based on human whims or cultural perspectives – it is objectively defined. 10 joules of energy in a cup of water at 90C is quantitatively the same as 10 joules of energy in a cup of water at 50C. However, the former is more useful since it can do everything that the latter can and more.

For a material, it can be envisioned as the measure of order – or disorder – of a system. A system of pure iron has lower entropy (less disorder) than a system consisting of a random mix of iron with copper, tin, and lead, perhaps. At the same time, a designed system where iron and chrome and carbon are in specific amounts in a specified manner has lower entropy (more useful) than pure iron. The system of pure iron is more useful than some random mix of iron, chrome and carbon. This mix has lower entropy (is more useful) than when shards of this alloy are mixed with plastic, paper, rags and host of other materials. The last system is usually a description of a waste stream. Again, the ‘usefulness’ of a material is not defined by the whims of people but by the amount of order in the material.

One needs energy to take a system from a state of higher entropy (high disorder, waste) to its purer form which has lower entropy and is more useful. One question that needs to be addressed is how much energy is required to cause this change. The other, perhaps more interesting question is, how much entropy is generated in affecting this change.

The *Second Law of Thermodynamics* – which states that the total entropy of any closed system (a system into which there is no input or output of energy or materials) cannot decrease – provides answers to the above questions. Thermodynamics argues that any process used to reduce the entropy of an entity (to develop a more useful article) will create more entropy (increased waste) in the surrounding environment within this closed system. Appendix 1 provides a more detailed description of such a closed system.

If one ignores the energy from the sun, for instance, Earth can be modeled as a closed system. This assumption is a good one, especially for processes where the source of energy is from within the Earth (for example fossil fuels, nuclear energy, and most industrial processes).

Implications

The implications of the *Second Law of Thermodynamics* are significant. The second law of thermodynamics is important to treatment of materials as well as processes. Any process that is used to decrease the entropy of a material also raises the entropy of the closed system. For example, consider the schematic in figure 1. It is assumed that the product is more useful than the raw materials – that is the reason for processing the raw material. From the perspective of the raw material, the product has a positive usefulness. Thus, the material undergoes a loss in entropy (with increased usefulness or value[vi]). But the second law says that the system must have an increase in entropy (decrease in usefulness) implying that there must be a waste stream with more increase in entropy (lower value) than there is decrease in entropy vis-à-vis the product. In plain English, the usefulness of the total system must stay the same or decrease. Thus, if one has a product with positive usefulness, there must be something else that has at least the same or more negative usefulness. That is, the waste stream must have significantly higher entropy (greater negative usefulness) than the raw material itself.

Consider the thermodynamic fate of the waste stream. Perhaps, another process can be designed to use the high entropy (negatively useful) waste material from the first process and convert it into a material of lower entropy (positively useful). However, the second law of thermodynamics requires that any closed system cannot decrease its entropy as a result of any process. This new process to treat the waste of the first will result in another waste stream that has even higher entropy (even more negative usefulness).

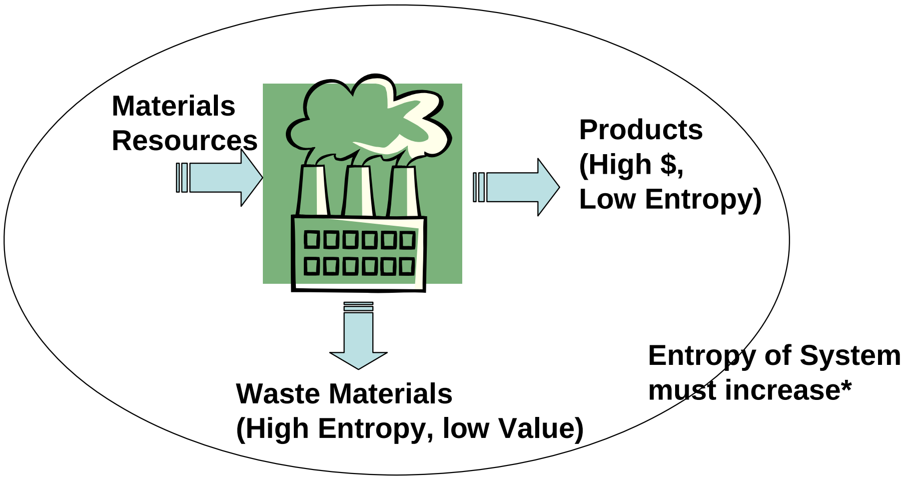

Figure 1. Entropy associated with a manufacturing process. (The asterisk points to possible exceptions described later)

Some direct implications of these results of significant importance to industrial planning and plant and process design follow:

1. Every process that produces higher value (lower entropy) products also produces greater amount of higher entropy. How do we address this stream? Where does it go? Who owns it and who is affected? These questions are not technological questions but questions that must be answered from policy and socio-political, even economic perspectives. This is an important question – often processes are built to help

communities or be of use to people; however, if a waste stream of negative usefulness is thrown into a certain section of the community, does the community have a net gain?
2. Industrial development, or mechanization, has a cost. For many years, the waste stream was dumped into oceans or land fills (which could be considered as infinite reservoirs). But now, large amounts of waste are being dumped and oceans, lakes and landfills cannot be considered infinite any longer. As the reservoirs are being affected, people are increasingly paying for it. One is forced to ask: “which processes are worth the waste they generate?” and “what is the impact of the waste?”
3. Numerous processes turn waste into gaseous products or into other forms – generally having much higher entropy (more negative usefulness) than the initial waste. Sometimes this form may be less noxious or can be used for as energy sources. However, as this thermodynamic analysis shows, such treatment of waste streams always results in products of negative usefulness. Often these processes also result in some of the most highly toxic chemicals known to humans.

Thus, the solution to the resource problem is not to just throw technology at it – greater processing invariable causes more entropy as thermodynamically proven, which translates to increased waste. And this is true of every process – whether chemical, biochemical, electro-magnetic, mechanical, or nuclear. At the cost of repetition, for any closed system, irrespective of the strategies used for waste treatment, there will ALWAYS be an increase in low value, negatively useful waste or pollutant stream. At best, technologies can change the form of the waste – and there certainly is value in that since some forms of waste are less harmful than others. It also lays to rest that nuclear energy does not produce waste – in fact it produces a huge amount of waste.

Technologies that are being deployed to help the world live better (more food, energy, etc) are actually hurting the world more than they are helping. These increased waste streams impact resources. They impact the ability to grow food and affect agricultural produce. They impact health of communities and subsequently their productivity and quality of life. Policies based on deployment of such technologies have high global economic and environmental costs.

The socio-political costs are also significant. As the cost of applying a technology increases, the technology is generally applied for that community that can afford it. At the same time, the high entropy stream from the process related to that technology will find its way to communities that cannot afford to use such technologies. That is, there is more high entropy waste than low entropy product (more negatively useful products than positively useful products) – yet we carry on since the low entropy product impacts a more socio-politically powerful section than the high entropy stream impacts.

For example, most urban wastes are dumped in smaller rural or semi-urban communities. It is true of cities in the USA, in South America and in India. For years in the past, waste was dumped in poor countries. These waste streams affect the agricultural produce in these communities, the health and productivity of these people and their quality of life. However, given that these communities are often economically disempowered or not important from a media perspective, it does not matter and we do not hear about the impact of this low value, high entropy waste and do not account for it in our analysis of technology feasibility. For example, how many of us know where the cities of Chennai[vii] (formerly Madras) or Minneapolis[viii] dump their solid wastes (high entropy streams from the sum total of urban processes)? Which communities gain from these technologies and which communities bear the cost?

Such a thermodynamic analysis thus shows that any future technology being envisioned today does not have the ability to resolve the resource, waste and related environmental problems that accost us (though they may help some of us move faster or some of us can have more personal climate control). Hoping for such a global solution based on such technologies is like hoping for the perpetual motion machine.

Qualifiers

There is one situation where our initial assumption of the Earth as a closed system *does not hold true*. For processes that are driven by solar energy, the energy source lies outside the Earth – and then, our analysis must change (presented in Appendix II). Processes that use the sun as their source of energy can have the total entropy of their system decrease. The ONLY way to design processes with lower entropy products without an increased higher entropy waste stream is by using solar energy[ix]. Even while stating this, however, it is noteworthy that not all solar driven processes will result in reduced entropy on Earth.

One example where entropy is reduced would be naturally growing plants being used to produce food. The process creates more useful products (food) while also using less useful composts with solar energy as an input. On the other hand, creating bioreactors that grow large colonies of micro-organisms to produce certain chemicals may not result in lower entropies even though the micro-organisms' activities may be solar driven. One reason is that often the building and maintenance of such bioreactors requires other processes whose energy is derived from elsewhere. Similarly, collection of solar energy by photo voltaic *may not* be an entropy lowering process *if* the process to make photovoltaic cells results in larger high entropy waste streams. So also, while long-term solar driven degradation of bio-stock to produce fossil fuels is an entropy lowering process, fuel based processes that produce bio-fuels may not be entropy lowering.

Solar driven processes do work or produce low entropy (positively useful) products even while driving down the total entropy. Thus, they can accommodate some other processes with significant high entropy streams while still keeping the total entropy non-increasing or increasing at very low rates. In addition, the waste stream of an ideal thermodynamic process is dumped into an infinite reservoir – that is a reservoir that it is unaffected by the waste stream. However, in real systems today, the waste streams affect the reservoir (which can no longer be considered infinite), thus reducing the efficiency of the process themselves. Solar processes keep processes closer to ideal and hence more efficient. Both these roles are significant from the perspective of sustainability.

Thermodynamic Analysis of Waste Management Policies

Perhaps the most straight forward application of thermodynamic analysis is of waste management technologies. The belief that somehow an engine can be used to *eliminate* waste has no thermodynamic basis. It goes against the second law – every new engine that attempts to address the waste stream will only create more waste. Having said that some forms of waste may be less noxious or less harmful than others and it is desirable to discuss these aspects while setting up such waste management technologies. Unfortunately, though, a thermodynamic analysis – perhaps the crux of any waste management technique – is not part of any technical planning.

Consider various components of waste and their processing. Food, yard and garden waste form one component of waste – and this is easily degraded by solar energy into soil, and CO_2 (which was part of the plant life cycle). This is one and perhaps the only component of urban waste that is sustainable from a thermodynamic perspective.

Paper is another component of urban waste. While many forms of paper are degradable as described earlier, and hence sustainable, increasing amounts of paper are produced using processes using hazardous chemicals – chlorine, for example and other dyes. Thus, if these forms of paper were now composted, chemicals leaching into the soil would make ground water and the soil toxic. Thus, most paper needs to be processed in other ways.

Other components of waste include polymers (which includes plastics and rubbers), ceramics (which includes glasses, fibers, composites), metals, paper (for reasons described), and electronic parts containing toxic chemicals. Various options are used to process these. First, however, they must be sorted. Some communities have users sorting these as they discard them – thus different cans for metals, plastics, etc. Some even sort plastics based on their composition, and this makes waste treatment more effective. In other communities, rag-pickers do the job. In both cases, from a thermodynamic perspective, the sorting is done through work that uses solar energy (human labor is based on food grown by solar energy).

Recycling is possible when certain waste components are combined, repulped or remolten to become raw materials for new products. This is possible with certain metals, papers and plastics. In both cases, the process does degrade the components; however, by mixing in some new raw materials and some fraction of new raw material, the product performance standards are maintained. Energy is needed to run this process and it is not solar-driven. In addition, there is degradation of materials. New raw material used in these recycled products is a significant fraction. All point to increased entropy.

Then there are components that cannot be recycled – and that includes many plastics, numerous alloys and composites, and electronic parts. Different communities handle these components differently. Communities that have had access to large tracts of land have usually resorted to landfills, where thousands of tons of waste are buried under the ground (in some sort of protective shell). It is assumed that over a long time, that waste will degrade into something we do not have to worry about or we will find a technology later to deal with it. Both premises are not appropriate – chemical leaching from landfills are affecting the land. We have yet to develop any technologies to deal with these landfills (though some suggestions of micro-organisms eating through such waste are being proposed). In addition, increasing pressure for land use is also affecting landfills as a strategy.

Some communities also dumped waste in the oceans but we do not really consider that a viable process for waste treatment.

Another strategy that was aggressively followed, especially in communities with little land, was to burn the waste. Given that there is a significant hydrocarbon component in the waste, people assumed that energy could be produced by burning it. However, many such waste streams were mixed in ways where the calorific value of the waste stream was no high and the process had to be subsidized to keep it going.

More dangerously, though, burning of these wastes produced dioxins – one of the most toxic chemicals known to humans. This resulted in laws requiring such units include very expensive control systems to detect (and burn) dioxins that were concentrations lower than parts per million and hence the use of such units have become limited in economically wealthy communities, though they continue to be foisted on less wealthy ones.

From a thermodynamic perspective, it is quite straightforward to see that any non-solar process to convert waste would result in more waste. Perhaps the nature of the waste would be less noxious (which may be a reason to use such a process), but more waste nevertheless. Yet, even as a new generation of waste to energy technologies is being proposed, there is no serious attempt to understand the thermodynamic implications of waste processes.

For one, such policies would require us to question levels of consumption – a topic that our society based on growing consumption is unwilling to discuss. Second, it would require life cycle analysis of products from a *thermodynamic perspective*. Today some companies do conduct life cycle analysis but assume that current modes of recycle and burning are apt solutions – clearly they are not sustainable from a thermodynamic perspective. In other cases, most companies claiming to use cradle to cradle approaches are only salvaging a small part of the materials used in their products for re-use – perhaps the most economically significant part.

A thermodynamic analysis of waste might also perhaps encourage us towards different ways of materials design – using materials that degrade into components that may be reused. One example would be the development of polymers that biodegrade into C4-C10 chains which could be sequestered for redevelopment of new polymers. One must remember though that while this would be recycling of materials, one would require new energy to reprocess them.

Clearly, though, thermodynamic analysis of these processes would point us in directions quite different from policies of today. It would engender different emphasis on technologies developed, different economic organization, different cultural mores.

Thermodynamic Analysis of Energy Policies

Hundreds of journal articles have been written on possibilities for non-fossil fuel based energy. Nuclear Energy. Bio-based energy from corn, from soybean, from cellulose, and numerous other sources. Articles exploring and addressing technical challenges as well as social, economic and political perspectives. Earlier paragraphs already describe the tenor or some of the discussions. It would be arrogant to claim that a couple of paragraphs can address what hundreds of thousands of pages attempt to describe.

Yet, this short discussion, in framing the discussion from a thermodynamic perspective, attempts to define the scope of what such energy alternatives can or cannot achieve. More specifically, are they sustainable alternatives.

The bio-based approach recognizes that fossil fuels are a fixed depleting source and hence presents that if organisms and organism-derived products could become energy sources, the source could be replenished simply by managing lifecycles. This is an important argument not just for energy but also for materials since fossil-fuels are also the source for petrochemicals which result in a broad set of products globally. The claim then avers that since the source could be replenished, bio-based energy could be a sustainable solution to the world's energy needs.

These arguments are presented with data regarding the energy required to produce bio-based energy and evidence suggesting that in comparison to petro-energy, this is more energy efficient. It also argues that it reduces the amount of greenhouse gases released into the atmosphere – even claiming that since this is based on growing plants (which use CO_2 as an input), this would even cause a reduction in greenhouse gases. Thermodynamics cannot compare bio-based and petro-based energy without much more detailed data – and that is the source of much controversy.

However, thermodynamics can be used to understand the sustainability of bio-based energy (and materials). While raw materials (cellulose, carbohydrates, glucoses) are converted to ethanol (for energy), the second law also demands higher entropy lower value products be produced in as much quantities if not more. While the bio-engineering aficionados can argue that more research will help take advantage of these ‘less useful streams’ to produce more useful products, there is no getting around the second law – increasing amounts of less useful products (waste streams) will be produced. Despite claims of sustainability[x], the second law says that these processes produce a high entropy waste stream larger than the low entropy product stream[xi].

What might these waste streams be? They might be as gas streams (oxides of nitrogen and sulfur) or liquid and solid streams. While these streams could be exposed to bacterial action and composting (as happens today with fallen trees and decaying leaves), the quantity and the quality (given the chemical processing) will be significantly different[xii]. Thus, larger volumes of bio-processing also results in larger volumes of waste streams.

Calorific value of charcoal is about 32000KJ/kg; that of cellulose is about 16000KJ/kg. The world today uses energy at the rate of 20 terawatts – we will use $2x10^7$kg of cellulose every second or need to dispose $1x10^7$kg of cellulosic waste every second. These waste streams – obviously processed to ensure that we can take advantage of any by-products - will affect quality of land, water and air. Where do we dump these? We know that industrial waste streams have affected the fertility of land and the potability of water. Chemical processing of bio-sourced materials create many similar molecules – bio-sourced materials are not necessarily more biodegradable. They will reduce the quality of land, water and air – so how are they sustainable?

Thus – while bio-based energy might be *more* sustainable than fossil-fuel based, thermodynamic analysis shows that by no means are they sustainable.

A similar analysis of nuclear energy is in order since it has been presented as ‘the green energy’. We know that nuclear energy is produced by bombarding a critical mass of certain radioactive atoms (Ur, Pu) with particles – in essence one is providing high energy (through kinetic energy sources) to these particles. In the absence of these conditions, the radioactive reaction is not spontaneous. Making this argument of non-spontaneity, one revisits equation 2 in Appendix I which says that the free energy of such a non-spontaneous process must increase.

$$g_{sf} - g_{si} = \Delta g_s > 0$$

This implies

$$\Delta u_s > \Delta T_s s_s$$

Yet, with some initial energy E provided to this system, the reaction becomes spontaneous.

$$g_{sf} - g_{si} - U = \Delta g_s - U > 0$$

$$\Delta u_s - U < \Delta T_s s_s$$

The energy of a nuclear reaction is in billions of Joules per gram. The initial energy is much smaller – as it must be for this to be a solution to be attractive. The reactor temperature is in the thousands to tens of thousands of degrees. Thus the entropy change due to such a process is in millions. Compare that with combustion of coal – the energy is in tens of thousands of joules per gram. The temperature is in hundreds to perhaps couple of thousand degrees centigrade. The change in entropy of such a process is thus in tens to hundreds of units.

In a nuclear reactor, much higher quantity of very useful energy is being created – which makes it so attractive. Thus, the waste stream (measured by the change in entropy) must also be higher than coal combustion based energy. Clearly the low use waste stream must be tens of thousands of times greater than coal based combustion – as suggested by the above second law analysis.

What is the identity of this waste stream? Nuclear reactors produce high volumes of highly radioactive and toxic by products including processing fluids, ores and other minerals that are associated with it, materials used in the reactors and for absorbing energy around the reactor, etc. All of these require special handling for they are much more toxic and bigger health hazards than greenhouse gases even in very small gram quantities. However, tones of these materials need to be disposed. An analysis that dismisses this waste stream is either incomplete or disingenuous.

Thus, while the nuclear industry is repositioning nuclear energy as the green energy, it is by no means harmless. It may not produce greenhouse gases but it has much more toxic and hazardous by products. It certainly does not provide a sustainable solution for our energy needs. While much of the discussion has been around the capacity of these reactors, their efficiency and the nominal cost of nuclear energy, most have not accounted for the waste streams – which are larger than from traditional sources (by metrics of entropy).

Those engaged in energy policy while arguing that bio-based or nuclear energy are feasibly sustainable alternatives for the world must evaluate these from a thermodynamic analysis such as one presented above. While these sources will provide very large amounts of energy, neither is truly sustainable and both produce very large waste streams (one, perhaps much larger than the other) that must be addressed. It is unfortunate that technologists have not presented this perspective and policy makers continue to harp on the sustainability angle of these forms of energy without accounting for questions about entropy.

Thermodynamic Analysis of Agro-policies

A thermodynamic analysis of agro-policies is quite different from an analysis of technologies. And yet, this makes the case that thermodynamics is a potent tool to understand how we utilize resources and the direction of development.

Thermodynamics argues that a necessary (though not sufficient) condition for the set of processes that are sustainable is that they must derive their energy from the sun (an energy source outside the Earth). These are the only processes that have the potential to reduce entropy. To the extent that they reduce entropy, they can complement other processes which use other energy sources.

We generate some (small) fraction of our energy from wind, waves and the sun's rays. That makes some impact on sustainability but it is minimal. We need to apply technologies and evolve policies that help these processes of energy generation.

A much more significant process of capture of solar energy is through *natural* agricultural processes – i.e. agricultural processes without the use of synthesized chemicals. Such natural processes help to develop biomass while causing a reduction in entropy. They provide energy for human and animal labor. By providing livelihoods to large population of people around the world, they allow for sustainable economic activities that support livelihoods.

Policies, however, are pushing for more mechanized agriculture that uses fewer people. Policymakers argue that more economic growth demands fewer people are involved in the agro-sector. This is a double-whammy from the perspective of sustainability. Chemical driven agriculture makes it less sustainable. Energy used in production of chemicals and the entropy generated in waste streams in production as well as application of these chemicals (in land and water) more than off-sets the gains in sustainability through the harnessing of solar energy in production of biomass. In addition, with more people shifting away from agriculture, more net entropy generating economic processes are needed for their livelihoods[xiii].

Agro-policies based on such a thermodynamic analysis would recognize that a large fraction of the population engaged in natural agriculture is the most sustainable option available and would help develop technologies so that they could access higher value agro-products in the supply chain. In addition, the elimination of all policies that subsidize the cost of waste streams from production, manufacturing and services – all of which actually impact agricultural conditions, and their produce. The political and economic realities today make such recommendations fantastical – however, from a thermodynamic perspective, there is no other option.

Conclusions

Future technologies – such as biotechnology and nanotechnology – are based on developing highly ordered materials, where molecules and cells are arranged just right. The thermodynamic arguments show that as the products are increasingly well ordered (have lower entropies), waste streams must have even higher entropies. We are already seeing this – the semiconductor industry is one of the most polluting industries. It has among the largest high entropy waste stream. Broad utilization of such technologies is not feasible in our world with growing resource limitation; such a model will actually reduce our access to resources (through depletion of our reservoirs), not increase resources.

Alternatively, this analysis concludes that only certain solar based technologies can be used without rapidly increasing the entropy on this closed system. Currently our society is designed on growth that is almost completely driven by fossil-fuel and nuclear energy sources. Solar based processes (agriculture) are being increasingly minimized and even there the process is becoming increasingly dependent on fossil fuel (pesticides, fertilizers, mechanization are all examples). A community that can sustain itself in the long term must be based on solar driven technologies to meet our needs.

That is not to say that a community can/should have no technology that relies on other forms of energy. It will use fossil based energy, or other non-solar sources. However, the waste streams that are generated by these processes must be balanced by much larger set of solar driven processes – else, the rate of entropy produced by these non-solar based processes will accumulate at a rate that is much higher than the rate at which entropy is reduced by solar processes.

Finally, there is also a realization that perpetual machines are impossible. Technology cannot solve everything – there is a thermodynamic limit. All (non-solar based) processes produce more negatively useful streams even though these processes are meant to produce positively useful products. With increasing rates of production and growth, these negatively useful streams are accumulating faster than the positively useful products, choking people and communities. There is only one thermodynamic solution – which is to use the only source of energy outside the Earth.

Appendix I: A Closed System

More formally, consider a system s that goes from an initial state i (waste) to a final state f (more useful state). The subscript s refers to the system. The entropy of the final state is lower than that of the initial state.

$$s_{si} > s_{sf}\ ;\ s_{sf} - s_{si} = \Delta s_s < 0 \qquad 1$$

Since this process has not occurred spontaneously (this assumption disregards the numerous processes presented in volumes of fiction through which waste spontaneously transforms into its pure forms), the free energy of this process must increase

$$g_{si} < g_{sf}\ ;\ g_{sf} - g_{si} = \Delta g_s > 0 \qquad 2$$

$$u_{si} - T_i s_{si} < u_{sf} - T_f s_{sf} \qquad 3$$

$$u_{si} - u_{sf} < T_i s_{si} - T_f s_{sf} \qquad 4$$

Let us assume that this is an isothermal process. This is not a bad assumption; non-isothermal processes can be approximated as a series of isothermal processes.

$$u_{si} - u_{sf} < T_s\left(s_{si} - s_{sf}\right) \qquad 5$$

$$\Delta u_s > T_s \Delta s_s \qquad 6$$

Since Δs_s is less than zero, let us say Δs_s is equal to some value $-k_1$ where $\left|k_1\right| = k_1$.

$$\Delta u_s > -T_s k_1 \qquad 7$$

There are two distinct cases.

Case 1: $0 > \Delta u_s > -T_s k_1$ 8

Case 2: $\Delta u_s > 0$ 9

Consider case 1. Assume that $\Delta u_s = -k_2$, where $|k_2| = k_2$. The free energy argument for non-spontaneity leads to

$$\Delta u_s > -T_s k_1, \text{ i.e. } u_{sf} - u_{si} + T_s k_1 > 0 \qquad 10$$

We thus need to provide some initial energy u_{E1} (i.e. increase the value of u_{si}) so that the left hand side becomes less than zero leading to the conversion of the system from state i to f. This is expected since the system did not spontaneously convert itself from state i to state f.

Similarly, for case 2, $\Delta u_s > 0$. Assume that $\Delta u_s = k_3$, where $|k_3| = k_3$. The free energy consideration for a non-spontaneous process leads to

$$\Delta u_s > 0, \text{ i.e. } u_{sf} - u_{si} > 0 \qquad 11$$

Again, some initial energy u_{E2} is needed so that the left hand side becomes less than zero and the process of conversion from state i to state f is achieved.

In either case, some energy u_E must be given to the system for the process to begin. Some engine E_{N1} must use work W to deliver energy u_E to system s at temperature T_s from reservoir R_1 at temperature T_1. The work W is obtained from engine E_{N2} and the process is shown schematically in figure A1. The complete process is defined by an overall system SYS.

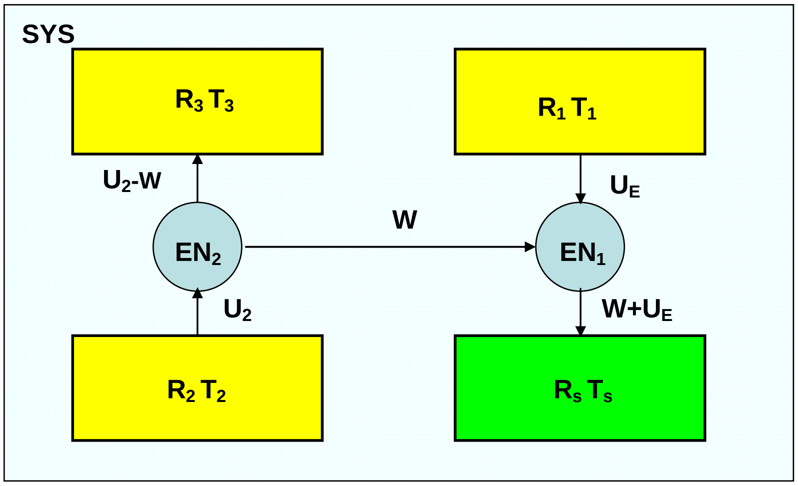

Figure A1. Schematic of Energy flow

Energy u_E has to come from another reservoir R_1. We assume that the temperature of the reservoir R_1 is less than T_s – the temperature of the isothermal process of the system. We know that the ultimate source of all energy on the Earth is the sun and the temperature of this energy reservoir (that processes on Earth can access) is the ambient temperature. If the temperature T_1 of reservoir R_1 is greater than T_s, then we will have to account for some other engine that takes energy from this reservoir at ambient temperature and converts it to this higher temperature. In which case, our assumption holds that finally, we have to access the energy u_E from a reservoir whose temperature is lower than or equal to T_s.

Thus, assuming that $T_1 \leq T_s$, as per the first law of thermodynamics,

$$\Delta U_{SYS} = 0 \text{ (which is seen to hold), and} \tag{12}$$

$$\Delta S_{SYS} \geq 0 \tag{13}$$

$$\Delta S_{SYS} = \Delta S_1 + \Delta S_2 + \Delta S_3 + \Delta S_s \geq 0 \tag{14}$$

Given that Δs_s is equal to some value $-k_1$ where $|k_1| = k_1$,

$$\Delta S_1 + \Delta S_2 + \Delta S_3 \geq k \tag{15}$$

Appendix II: Energy from the Sun

Let us however consider a reservoir that provides energy and lies outside the system and its surroundings. This reservoir, in the case of earthly processes, is the sun. In that case, there is a significant difference in the thermodynamic cycle as shown in figure A2. In this case:

$$\Delta S_{SYS} = \Delta S_S + \Delta S_2 + \Delta S_3 ;\; \Delta S_{SYS} + \Delta S_{R1} > 0 \tag{16}$$

Δs_s is equal to some value $-k_1$. In addition, reservoirs 2 and 3 along with their engine for an independent Carnot engine which must obey their own 2nd law requiring that $\Delta s_2+\Delta s_3$ is some positive value k_4. Thus,

$$\Delta S_{SYS} = k_4 - k_1$$

Thus, there can be situations where Δs_{SYS} is less than or equal to zero implying that less (high entropy) waste is produced in the process. The only feasible process where one can recycle a 'waste' (some system with high entropy) without creating more 'waste' (i.e. generating more entropy than one set out to remediate) is when the process uses energy whose source is the sun. Alternatively, under these conditions, one can create products of greater value (lower entropy) without producing waste of much lower value (higher entropy). Examples include growing of plants or other organisms that converts low value wastes to biostock or enzymes that degrade wastes.

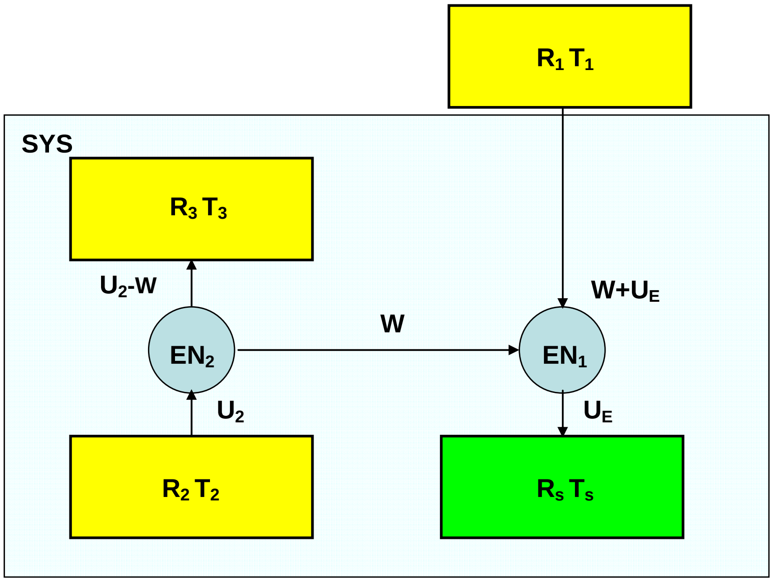

Figure A2. Schematic of energy flow with external reservoir.

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i Paul Brown, The Guardian Weekly, 12/8/05

ii World Nuclear Association, 2005. Nuclear Power in the world today. Information and issue brief, January 2005.

iii William Keepin. On costs and limitations of a large-scale nuclear power programme. Greenpeace, OUP 1990. ; Peter Bunyard, Taking The Wind Out Of Nuclear Power, The Ecologist, UK, http://www.nuclearpolicy.org/index.cfm?page=Article&ID=2601

[iv] Committee for the Study of the Economics of Nuclear Electricity, UK: 1981 Report; Dale Vince and Terry Macalistair, The Guardian, 19/9/02.

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[v] Even today though, there are people trying to create perpetual motion machines. However, they get little attention and certainly do not get millions of dollars to make it work. Nor are policies made for future transportation based on such outcomes.

[vi] In the above section, the use of the term 'value' is not a slip, nor is it a sleight of hand. Consider any material. If it formed spontaneously (as per the second law), it would be easily available and of limited value. Often a process is focused on taking a material that exists in nature (formed spontaneously or as a result of natural processes) and increasing the value of the material by increasing its usefulness. In other cases, processes take other processed materials and then adding more usefulness to it. The greater the order of material desired, the more processing it needs and more is its usefulness and more the value.

[vii] Chennai dumps its waste in what was once a fertile part of the state in the region of Cuddalore since it has significant sub-surface water (unlike many other parts). Now the area is highly polluted with agriculture becoming very limited and serious health concerns.
http://www.thesouthasian.org/blog/archives/2005/air_in_cuddalore_unfit_to_brea.html

[viii] Minneapolis rates itself as one of the most forward looking and environmentally conscious cities in a progressive state of Minnesota, in the USA. Yet, it relies on the neighboring states of Iowa, North Dakota and Wisconsin to dump its wastes in landfills.
http://www.pca.state.mn.us/publications/reports/lrw-sw-1sy06.pdf

[ix] There is another set of energy sources within the Earth that could be used without an increase in entropy. These processes occur within the Earth naturally – wind, volcanic action and geothermal activity, tidal processes, lightning are all examples. Each of them is a source of energy – some more feasibly accessed than others. In each case, the energy itself is available whether used or not. And it is dissipated over space and time, even if one does not tap into it. Thus, it is a ready source of energy. If one builds an engine that can tap this energy to do work, the engine will give up some waste heat. However, even if one did not build an engine that could tap one of these sources, the energy would dissipate into waste (heat, sound, etc). The question of sustainability in this case is in understanding the form of engine built to tap into these energy sources and what one did with the energy. Thus, if one built wind vanes from materials in ways that resulted in large amounts of waste, then one has to deal with large waste streams and the method of use of this energy results in increase in entropy.

[x] In purely thermodynamic terms, sustainability would be defined as condition of non-increasing rate of entropy.

[xi] Some proponents have argued that bio-fuels are cleaner than fossil-fuels and that may be true. This discussion does not negate that claim. However, to the extent that sustainability is based on the absence of net pollutants (or reduction of entropy), bio-fuels are not a sustainable solution either.

[xii] Processing of biomass for fossil fuels occurred over millions of year through solar action – thus the 'waste stream' was recombined to achieve low entropy high useful products (more plants) besides the fossil fuels.

[xiii] While the sustainability argument is a powerful one, it cannot be used to oppress communities into behaving in specific ways. Thus, if people wanted to leave agriculture to do other things, one cannot force them – though policies could evolve that does not subsidize externalities from other activities. However, in this case, with thousands of campaigns being waged by displaced farmers and their families demand access to their lands and livelihoods, clearly alternative economic opportunities are neither easier to come by nor are they preferred.