Rocketing to Energy Sustainability

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Abstract

Metaphors are an important way to facilitate understanding of new processes. This metaphor is constructed based similarity of a rocket's and civilization's transition from one stable state to another at a higher level accomplished using a limited supply of fuel. For example, fossil fuels enable the transition from sustainable pre-industrial society to another more advanced sustainable society. However, to realize this potential, society must transition to a sustainable energy supply since fossil fuels are dwindling. A major question is whether this global transition can be completed at the same time that global development continues to improve lifestyles and economic opportunities. To help understand some of the complex relationships and challenges in this transition, a metaphor is developed of the evolving technological society as a rocket, which once launched, needs to reach a critical velocity and altitude before obtaining a sustainable orbit. The basis for the metaphor is that there are two stationary locations for the rocket- the ground (pre-Industrial society) and a stable orbit (advanced technological society). The rocket transitions between the two with technology to utilize a finite amount of fuel to overcome gravity and atmospheric friction to attain a speed, altitude, and orientation for a stable orbit.

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Introduction

Technological civilization depends on large energy flows but its current major energy sources from fossil fuels is dwindling. Much economic progress was made in the 20th century with the energy generated from burning fossil fuels improve the quality of life for many (Smil 1994, Yergin 1991, Yergin 2011). However, to continue on a successful path, civilization must transition to a sustainable energy supply. This transition involves a balance of increasing energy demand (from both increasing population and lifestyles) with the new energy sources and improved efficiency. However, the higher quality of living often results in a decreased (or negative) population growth rate (Korotayev 2015). A major question is whether this global demographic transition can be completed at the same time that the world's energy transitions from fossil fuel to renewables. If energy resources dwindle before the demographic transition is complete, economic foundations may crack.

Metaphors are an important way to facilitate understanding of new processes, such as the approach to sustainability (Alden Trust 2011, Steffan 2007, Larsen 2011, Karlsson 2015). .An evolving technological society can be viewed as a metaphoric rocket (Karlsson, 2015). An important addition to this metaphor is the consideration of the rocket reaching orbit. A rocket, once launched, needs to reach a critical velocity and height before obtaining a sustainable orbit. Once a stable orbit is attained, there are many further beneficial options such as space observations or facilitating further space exploration. The basis for the metaphor is that there are two stationary states for the rocket- the ground and a stable orbit. The ground is analogous to the historical situation of a society based on traditional solar energy for crop growth, warmth, wind, and water. The stable orbit is analogous to an improved situation of an advanced society with more freedom, comforts and fulfillment, which is also stable through technologically capturing a larger fraction of the solar energy (or supplementing it with nuclear fission or fusion).

The process of getting a rocket into orbit requires:

1) Developing the rocket technology including engines, fuel, and crew compartments;
2) Launching the rocket against gravity;
3) Climbing through the atmosphere;
4) Shifting the orientation from vertical to horizontal; and
5) Attaining enough directed speed and altitude to obtain a stable orbit

The metaphor is that society must generate enough technological progress to again generate sustainable energy (from solar or fusion sources). This transition from the sustainable preindustrial agricultural lifestyle to an advanced technological lifestyle is facilitated by the temporary use of exhaustible fossil fuels.

These stages might correspond to historical periods of:

1) Developing: the scientific & industrial revolution;
2) Launching: World War II;
3) Climbing: the Cold War and Oil Crisis;
4) Shifting: the current period of addressing entangled issues of climate change, demographic transition and energy transition; and
5) Attaining: the increased use of renewable energy to sustain the process of global convergence.

Also, it is not clear if society's transition to energy sustainability (the metaphorical stable orbit) will be completed successfully (Ausubel 1999). For example, fuel could run out or a fundamental flaw could disrupt the process.

The paper is organized starting with a brief description of relevant history with a focus on energy use, followed by the metaphorical connections, and finishing with some possible ways, based on this metaphor, to track the progress to sustainability.

From medieval energy sustainability to today

The traditional agricultural society of the Middle Ages in the early 14th century suffered through many problems. People worked hard to harvest enough resources such as wood, food, and metals to support their agricultural lifestyle. The energy from food and wood was supplemented by the energy of domesticated animals, and occasionally from water and wind for mills and transportation. Slavery which had been prominent in the Roman Empire had greatly diminished but still peasants had relatively little freedom to move or innovate in feudal society. Medicine, entertainment, and education were inadequate or ineffective. To add to the burden, fighting would often break out between the feuding feudal lords, who were obligated to protect their serfs.

However, increased interaction between geographically separated societies through trade and conflict opened new possibilities. Trade along the Silk Road increased interaction between Europe and China, leading to exchange of inventions, although many (including paper, gunpowder, and the compass) came from China. Invasions from central Asia, such as Genghis Khan's Mongols, caused more than exchange of ideas and items. Diseases, such as the Black Death in the mid 1300's, spread along with trade and Mongol invasion. This plague triggered changes in the society structure as labor became more valuable.

After the Black Death, questions arose concerning the reason for the tragedy. Society changed via shortages of labor but also in terms of questioning the teaching of the classics such as how the heavens moved. It was common knowledge that the Earth was round and with a good estimate of its size by the Greek Eratosthenes in about 200 BC by observing shadows at different latitudes. Copernicus was motivated to hypothesize that the planets went around the sun. Later measurements by Tycho Brahe led Kepler to analyze the planet data and show it followed a simple mathematical pattern not only in space but also in time. This motivated Galileo to explore the planets even further with the new invention of the telescope which he travelled to Middleburg to buy and then reproduce. With this he was able to see the moons of Jupiter and saw the phases of Venus, clearly showing that these bodies did not circle the Earth but instead that the planets orbited the sun and that many planets had their own moons. Newton then synthesized the nature of gravity on the Earth (falling apple) with the motions in the Heavens, the natural orbits. Others explored different questions. For example, alchemists wondered how one form of matter could be changed to another. While not finding the philosopher's stone to turn lead into gold, they laid the foundations of chemistry.

However, few imagined that basic science information might transform the way humans lived. Earlier innovations, such as Hero's engine in the first century, were not further pursued since such power devices could not effectively replace the relatively inexpensive human labor. By the early 17th century, Francis Bacon advocated skepticism about knowledge not gained through empirical approaches. His empirical observation method would contribute to the development of the scientific method, which also considers the importance of theory and hypotheses.

Already at this time (early 17th century), energy supply was already not sustainable. An energy challenge arose when forests diminished as wood was needed to convert into charcoal to support the higher temperatures to processes increased iron production. Coal was a potential substitute for wood to heat but it was dirtier and could not sustain the conditions for iron working without a special furnace.

The industrial revolution started in England with innovations in the interdependent technologies of iron, railroads, and coal mining. The increasing demand for rails and steam engines resulted in greater demand for iron, which required increased coal mining for operating the engines and processing the raw iron. The more intensive coal mining then required more steam engines to pump the water from the mines and railroads to transport the coal, thereby completing the cycle with an increased demand for iron.

The industrial revolution also brought major challenges to society as factory systems developed, urban areas became more densely populated, and pollution effects were experienced. To open up the potential to a wider group, human rights and principles of democracy and free markets were developed throughout the scientific revolution and industrial revolution. For example, Ben Franklin participated as a leader in both scientific areas (such as electricity, optics, and heat flow) and civil society (with participation as a founding father, diplomacy and setting up social institutions such as fire departments and libraries as well as deriving most of his money through newspaper publishing). However, life at the end of the American Revolution was much the same as both political and scientific principles needed to be expanded and applied.

The U.S. Civil War demonstrated the technology and societal changes from the coal-based industrial revolution. Technologies such as rail, telegraph, guns, and iron ships were tested along with democratic principles against slavery, regional rights, and free market industrialization transitioning from an agricultural system. Further tests occurred during World War I with the introduction of technologies such as air planes, chemical warfare, machine guns, and submarines along with the introduction of new societal processes such as the rights of military conscription and colonization. However, technology exuberance and over speculation led to an economic collapse (the Great Depression). The stresses during the economic downturn allowed groups espousing various solutions such as communism and fascism.

While oil had been known since early civilizations, it had been treated almost as a nuisance. The demand for city lighting after the Civil War encouraged exploration for substitute for candles. Whale oil from sperm whales served this purpose for a while but the supply could not keep up with the demand. Kerosene, a byproduct of oil refining, was identified. However, it could be dangerous if not prepared correctly. John Rockefeller developed a process that led to a standardized kerosene (Standard Oil) that could be safely transported and used.

The oil was supplied from Ohio and Pennsylvania by rail and then by pipeline. Other areas (such as Texas, the Middle East, Romania, the Caucasus, and Indonesia) were explored for oil resources to keep up with the increasing demand. The new machines of industrialization required access to oil so each country vied for control of oil fields, however, the U.S. maintained an early development lead.

A major factor in World War II concerned access to resources. Large feedback loops continued to grow- more technology led to better tools and larger energy demand, leading to new technological solutions. New technology was developed throughout the war including radar, jets, computers, rockets, electronics and nuclear. Pressures to use human resources to a greater potential resulted in expanded participation to women, minorities, and former colonists. Soon after the war's end, a promising technology, nuclear fission power, seemed to offer a seemingly inexhaustible inexpensive energy resource to replace the need for fossil fuel. Some claimed nuclear generated electricity would soon be "too cheap to measure" after implementing breeder reactors that would generate more fuel than used.

The environmental movement hit its peak in developed countries at about 1970 with NEPA in the U.S. as a reaction to oil spills, contaminated waterways, smog, and chemical disposal sites like Love Canal. The green revolution in India was coming to fruition recognized in the 1970 Nobel Peace Prize to Norman Borlaug. In the middle of the 1970's the U.S. hit the halfway point of oil extraction, while in many other places exploration boomed. However, the increased oil demand also enhanced power of other oil producing countries who formed OPEC to control the production and thereby also the price. Two oil price shock waves went through the economies in 1974 and 1979, quadrupling the price of oil. The transition was difficult but increased investment in energy efficient technologies eventually reduced the needed fossil fuels for tasks by about a half (LePoire 2004, 2010a, 2010b). This energy efficiency slowed the demand for oil so that by the mid 1980's the price of oil had decreased enough to hurt oil producing countries like Russia. The economic strain from the oil price drop contributed to the fall of the Soviet Union. But also about this time in the mid 1970's the economy started to shift. In the Real Progress Indicator which starts with the GDP and then subtracts economic activity that is counterproductive and adds the value of outside of market activities. This indicator peaked in the mid-1970s even though the GDP continued its exponential climb (Kubiszewsk 2013) .

- Population explosion with medicine and ag revolution India
- More oil found but U.S. hits halfway in the 70's, economy boomed
- Frictional Cold War saps resources and

hunt for new energy
- Electronics developed and miniaturized
- 70's correction: energy crisis, real GDP and wage stall, computers enter

In the early 1970's it was believed that nuclear power was to replace oil as the primary energy source, but this technology was slowed down due to security, financial and environmental issues. Another form of nuclear energy fusion seems to promise more energy with fewer complicating issues. However, it has been very difficult to control and always seems to be about 30 years in the future (the next generation). While nuclear fission energy is still being explored and new technologies exist to greatly mitigate the problems of the early forms, only Asia seems to be interested in pursuing this. It is unclear is more commitment to safe development would have allowed the developed world to quickly attain sustainability and then transfer it to the developing world. Currently nuclear energy can be viewed as insurance since it is still unclear whether renewable energy sources such as wind and solar would lead to economical sustainability (before fossil fuels are gone).

Control technology (electronics and computers) have greatly improved recently. In the early parts of WWII electromechanically devices were used for simple calculations. These were replaced with vacuum tube technology, followed by semiconductor transistors. These were then integrated to greater extents, following the Moore's law of improvement such that the capability of the integration was doubled almost every 1.5 years. While technology has often been identified as the fourth factor in economic growth with labor, land, and capital, a different analysis suggests that it is energy availability that explains this additional aspect to growth (Ayres 2008).

The rate of technological change may be slowing down. If the rate continued to increase, we would expect technology leaders to maintain their place because they would be able to innovate faster than existing technology diffuses. However, it seems like technologies are expanding throughout the world based on production with low labor costs followed by the advance into a higher quality of life. In addition, technological leaders are appearing outside the original first world, e.g., Korea, China, and India. An effect of diffusion outpacing innovation is seen in the work by Korotayev (2015) who found a correlation between the population growth rate and the gap in economic wealth. The population explosion in the 20th century is beginning to stop and in some areas such as Western Europe reverse. The world still has a long way to go if economic equality is attained. For example, the U.S. uses about 20% of the energy resources for 5% of the global population. This would mean that if everyone used energy at this rate the amount of energy would be 4 times the current demand.

We are in the process of determining whether this energy transition can be done. Learning curves for wind and solar technologies show that the cost of production reduces by a factor for every doubling of production. This cost reduction is driven by improvements (learning) in the production process. The variability of many renewable sources due to night, clouds, calm weather necessitates an ability to temporarily store energy when it is produce. The distributed nature of renewables, e.g., on each house also requires building a smart grid that can monitor the changing environment of production and consumption at each location. Environmental impacts of operation or throughout the life cycle is being monitored to ensure that unintended consequences might be identified and mitigated early.

Metaphor

The main metaphor is that just like a rocket, the society that advances with fossil fuel is initially on an unsustainable path (Figure 1, Table 1). After launching from the safety of the ground (leaving early agricultural sustainability), there is another sustainable situation – the orbit for the rocket and the use of technologically enhanced renewable energy for the society. Both systems, rocket and civilization, have to reach the second stable situation before their limited amount of fuel runs out. There are also many similar issues such as achieving stability, transitioning to new stages (phases), and the passing through the atmospheric friction (GHG release).

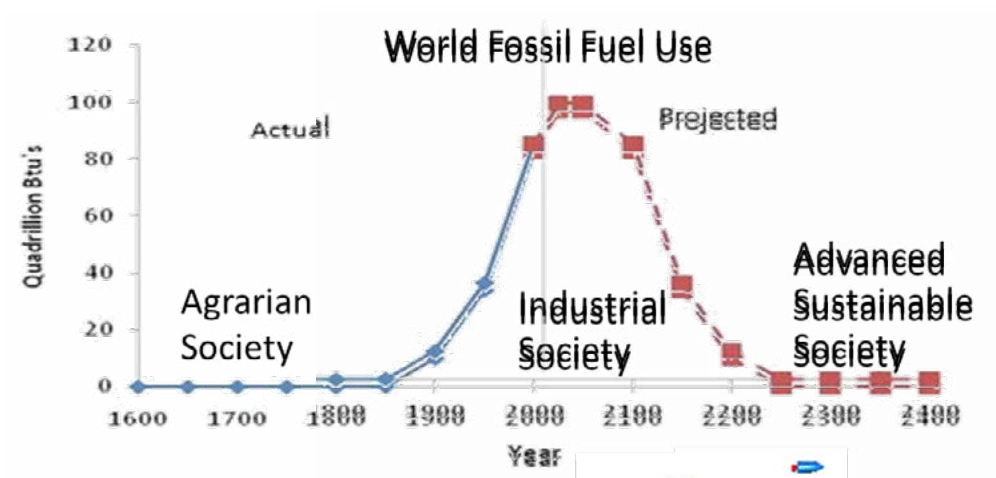
First, the situation of a successful launch into orbit includes aspects of preparation, launching, achieving stability, surviving atmospheric friction, flight planning, and obtaining orbit will be discussed. Each aspect is discussed first with the description of the rocket's process and then the aspect compared to a society transitioning to energy sustainability. Then ways that launches can be unsuccessful will also be discussed for the rocket and society.

Technology Preparation

Early engineers were skeptical of even being able to sustain heavier than air flight by humans. After the Wright brothers' demonstrations of manned air plane flight, others dreamed of designing rockets for space exploration. Unmanned rockets had been used in warfare and for fireworks. Some early pioneers tested principles of stability, control, and flight plans, sometimes failing spectacularly before the principles were understood. An early rocket design by Goddard for, example, had the engine on top of the fuel tanks leading to instability. Similarly, people at the start of the scientific revolution often did not foresee the potential of technology to transform society

Crew compartment Preparation

The counterpart to the Enlightenment is that besides the science, manned human spaceflight needs consideration on the crew compartment and conditions. The construction of the university system to not only pass along knowledge but to test and further science through research is similar to astronaut training to maintain, diagnose problems and fix the rockets components when needed.



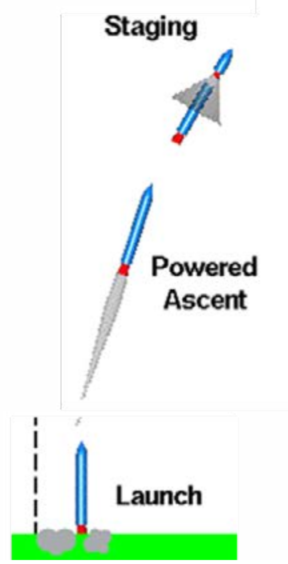


Figure 1. (top) Fuel use in both transition in transitioning society from one sustainable economy (agrarian) to another (advanced sustainable) and in launching a rocket into orbit (bottom)

Lift-off

For liftoff, the rocket engines must generate enough thrust just to overcome gravity. For example, if the rockets generated a thrust equal to that of gravity, the rocket would go nowhere. The thrust needs to be concentrated so that it is larger than gravity to be fuel efficient.

The fossil fuel society achieved "lift-off" during World War II by burning the fuel at a high enough rate to overcome a stagnant economy. The effort put into the innovations during WWII in radar, jets, nuclear, and electronics led to a positive feedback loop- the improved technology generated possibilities of further improvement. At the same time, oil resources were being explored and developed throughout the world.

Stability

Rockets are most vulnerable at lift-off because the speed is low and any small deviations from vertical up can be amplified. This has been observed in many early rocket attempts where the rockets chaotically loop around before crashing. However, once the rocket has gained some speed but still in the atmosphere, there is a natural feedback to vertical stability if the center of mass of the rocket is higher than the center of pressure. The fins at the bottom of the rocket are one way to increase the stability.

The orientation of world development was set by the winners of WWII who still argued over the ideologies of democracy and free market economy versus communism's single party and controlled economy. In a sense two rockets- one from the West and the other from the USSR raced to demonstrate their superiority. Only after about 50 years of testing did it appear that the Western approach with corrective feedback in the government and economy was stable. The rocket's velocity is then similar to the speed of economic growth, and the rocket's stability condition is similar to the automatic feedback mechanisms.

Atmospheric Friction

To avoid overheating from friction with the atmosphere, rockets launch vertically to quickly go through the atmosphere and only then align with the perpendicular orbit. The friction might be considered the counterpart of the potential overheating with greenhouse gases. Soon after the "lift off" during WWII, the release of GHG for a task was much larger. Now that we have learned how to handle energy efficiency, there is less GHG (friction) as we approach orbit.

Flight Plan

But once the lift-off is successful, how should the flight plan proceed? One space flight plan aims directly for the object of interest, e.g., moon or planet. Other plans use Earth orbit as a place to stabilize before moving on to other interesting locations. Then the transition to the flight to the moon is achieved by timing the firing of smaller engines to use the orbital speed to its advantage.

The direct flight plan is similar to those who want to realize ever increasing technological change (Kurzweil 2006) without first achieving energy sustainability (i.e., all fuel is used in one dash without achieving stability first). The second flight plan is similar to having a goal to reach energy sustainability but realizing once there, it is easier to solve other problems and move on to other interesting places. This allows some decoupling of the issues of technological change and energy sustainability.

Multistage transitions

With rockets, there are often multiple stages each with their own fuel supply and rocket engines. The first stage if often the largest since it has to lift the whole rocket off the ground. When the fuel is exhausted, the engine and the empty fuel tank are discarded.

In the metaphor, the stages are the different levels of technology. It is know that technology has proceeded in cycles such as the Kondratieff cycle of approximately 70 years. The early cycles of this were the railroad, coal and telegraph. Later oil was used with the internal combustion engine along with radio. The latest still uses fossil fuels but with much better efficiency and improved communicated through the internet.

Differences

It should be noticed that there are important differences in the transitions of society and an actual rocket. Rockets are often multi-stage meaning that the lower parts of the rocket are jettisoned after the fuel has been exhausted. This reduces the mass of the rocket to ease the work necessary to achieve the orbital velocity. However, in contrast the transition to sustainability seems to occur as more of the world's population joins a developed lifestyle with its increased demand for energy. In the metaphor, this could be viewed as adding mass to the rocket as it climbs, which then requires more work to obtain a stable orbit.

Possible Failure Mechanisms

It is not clear if society's transition to energy sustainability (the metaphorical stable orbit) will be completed successfully. In this metaphor, it is not at all clear which plan we should follow towards sustainability since we really do not know the fundamentals that any rocket engineer would know. Such information would include the weight of the rocket, the efficiency of the engines, the amount of fuel, the speed necessary to get into orbit, and the height of the orbit such that the atmosphere is negligible.

A rocket launch can crashing from loss of stability, fuel tank explosion, too slow acceleration leading to inefficient use of fuel, too much acceleration

Category	Rocket	Civilization
Stable States	Ground /Orbit	Medieval Sustainable/ Advanced sustainability
Fuel Limit	Tanks	Fossil Fuels
Self-Correcting Orientation	Center of mass above center of pressure	Free market / democracy
Concentrated Thrust	Big rockets with acceleration above 1 g	Technology feedback / acceleration
Withstand atmospheric frictional heating	Heat resistant material with proper course	Avoid large climate change
Attain orbital speed	Multistage rockets	Renewable energy with multistage of technologies
Possible Outcomes	Crash, run out of fuel, overshoot, orbit	Crash, run out of fuel, technology runaway, sustainability
Benefits of Orbit	Satellites, solar power, place to easily continue	Advanced lifestyle, ability to continue

Table 1. Comparison of various aspects in the metaphor of a rocket launched into orbit and society transitioning to energy sustainability.

damaging engines,. The rocket might also heat up too much when going through the atmosphere or if the orbit is too low. The rocket might not orient correctly for a stable orbit. Another failure would be for the rocket to enter a stable orbit but lose the capability to support humans, e.g., buildup of carbon dioxide as started on the ill-fated Apollo 13.

There are clear similarities in the transition to sustainability:

Loss of stability: A Rocket maintains stability through self-correcting as long as the stability condition is met that the center of mass is atop of the center of pressure. Similarly, if processes are not in place for self-corrective actions, progress towards sustainability could be lost or reversed. Such processes are fair markets in a democracy but with regulations to ensure market failure mechanisms are addressed. An example of a market failure might be the pricing of fossil fuel without including external costs such as pollution or defense to protect the international trade. The incorrect price signal would tend to encourage the movement towards the cheaper "subsidized" fossil fuel over renewables. This would be similar to the rocket losing its stability to continue in a vertical direction.

Fuel tank explosion: A rocket's fuel tank might leak leading to a catastrophic failure. While the oil underground could not immediately explode, there are scenarios where much of the energy might be lost, for example through resource wars at an expanded scale compared with WWII. All the oil would not have to be rendered inaccessible because the oil trade can be very sensitive to decreases in supply. The reduction in oil supply was seen during the Iran-Iraq war, the Iran embargo, and the burning of the oil fields during the Iraq war.

Acceleration too slow: A rocket launch requires a concentrated use of fuel just as the transition to sustainable energy relies on support for continuous technology innovations. If no technology advances are made, the society will not approach sustainability but instead just burn the fossil fuel until it is gone.

Acceleration too fast: The similarity to too much acceleration happens if the technological change goes too fast. This could strain the developing infrastructure. For example, if cybersecurity does not keep up, large damage might be done to the use of the smart grid. Other potential pathways include advanced technologies get in the hands of the wrong people leading to social instability. This high technological acceleration could result if the technology singularity happens. Safeguards are being proposed to mitigate these unintended consequences.

Atmospheric heating: A rocket experiences friction with the air in the atmosphere as it climbs and also in orbit if the height of the orbit is not great enough. This is similar to the transition to sustainable energy as we use fossil fuels that is generating potential GHG that leads to climate change. This suggests that it is important to reach the energy sustainability before the irreversible harmful effects occur, and that the sustainability is complete enough that fossil fuels aren't needed to fill an energy gap.

Incorrect Orientation: The orientation of a rocket needs to be change from the vertical takeoff to the horizontal when it reaches orbit. In orbit, the forces of gravity are just enough to balance the natural tendency to go straight (centripetal force). This is similar to the need to rethink the energy generation, distribution, transmission, and pricing to guide a sustainable energy transition so that the trickier balance of supply and demand satisfied.

A problem would occur if the variable solar and wind energy replaced all the electrical energy at present. During windy sunny days the lines would be overloaded and the energy not used. During quiet nights the lack of energy supply might cause brownouts. This balance can be achieved with proper storage and price incentives.

Loss of life support: Many problems in the Rocket's capsule might lead to an unsuccessful mission even if the rocket attains orbit. In the transition to sustain energy it is important to keep social and international tensions at a minimum despite the added uncertainty caused by the change. An example would be the potential conflict over water resources. Energy can be used to generate clean water from alt or polluted water through evaporation and efficient recovery of the energy after condensation. Another failure might be that technology is not shared adequately among nations.

Dashboard

To have a successful launch into orbit, many engineers, controllers, and astronauts work together to design and then monitor progress so that changes can be made to correct problems. Currently we do not have a set of equivalent monitors or controls. In many cases we really don't know the characteristics of the systems, e.g., the amount of fossil fuel, the Co2 level that causes irreversible harm, the number of people that need the energy, the level of energy efficiency that is attainable, the economic viability of renewable energy sources.

The transition to sustainable energy seems to have started (lifted off) with some self-correcting systems like market economy and democracy. It also had undergone a few changes in technologies (stage separations), for example dramatically increase energy efficiency. But only now do the possible criteria for reaching a sustainability such as total energy demands and technologies (stable orbit parameters such as height and speed).

This suggests some indicators for the dashboard:

A measure of the amount of fossil fuel remaining, similar to the rocket's fuel gauge.

A measure of strength of the self-correcting stability system in economic and political stable (rockets stability condition).

Comparison of GHG emissions compared to what the global system can sustain. (Comparison of the temperature to what the rocket can sustain.)

A measure of the global social stability and political will. (The cabin environment).

A measure of the projected demand for energy as the population increases and the lifestyle improves for many. (The mass of the payload.)

What level of renewable technology is required to supply the demand. (The required height of the rocket to escape frictional forces.)

How to encourage the implementation of the technology to generate the required demand. (The speed and reorientation of the rocket to achieve orbit.)

Some indicators have been defined and are beginning to be tracked (Henderson 2012 , U.S. Interagency Working Group on Sustainable Development Indicators 1998 , Ness 2007) including some specifically designed to help assess new potential energy technologies (Evans 2009). Others deal with environmental sustainability. For example, environmental impacts include those that affect air quality, food, water, disease, and land use. An attempt to outline basic environmental measures was made in 2009, with the nine planetary environmental boundaries which include natural resource use (land and water), atmospheric disturbances (ozone, climate change, and aerosols), and releases impacting biological activity and diversity (ocean acidity, chemical pollution, phosphorus, and nitrogen release). Estimates were made for each boundary's natural level, the current level, and the level at which impacts might rapidly rise. Some of these already have impacts much greater than their boundary action level, while a few others have greater uncertainty with undefined boundaries (Rockstrom et. al. 2009).

Conclusion

A metaphor was constructed for civilization to reach energy sustainability by comparing it with the process of getting a rocket into orbit. The basic metaphor was that the two systems transition from one stable state (subsistence farming and ground) to an elevated dynamic stable situation (enhanced technology energy sustainability and orbit). This transition is done with a finite amount of fuel.

The various phases were analyzed and compared including planning, lift-off, stability, heating, speed, and orientation. Potential negative outcomes were identified such as not enough fuel, accelerating too quickly or too slowly, and being conscious of maintaining a human livable environment. A potential dashboard of current indications was abstractly developed based on this metaphor but its realization would require much further investigation.

This metaphor might be a way to communicate the complex situation in approaching a sustainable state. The consequences can be visualized and the dashboard would provide some feedback on the critical criteria that need to be satisfied for successful attainment of sustainability. Just like the rocket in orbit however, the attainment of the second stable state is not the end of the adventure but instead a temporary transitioning point to further exploration and advances.

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