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THE CASE FOR SPACE

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ABSTRACT

This paper was written with the hypothesis that the earth was running out of non-renewable energy sources, and that off-world-resources, specifically metals from the moon and Near Earth Objects (NEOs) would be critical in transitioning to renewable energy sources. A projection of energy needed to raise and maintain an adequate worldwide standard of living over the next fifty years is compared with projections of future energy sources and the requirements to transition to renewable energy sources are noted. As it turns out, the needed technologies are at hand, but certain "energy metals" that are key to generating and storing energy efficiently are lacking in the earth's crust. These metals, namely the platinum group, uranium, thorium, cobalt, and nickel, were deposited on earth by asteroid impact and the near side of the moon and NEOs are prime locations for mining an adequate supply. To that end, this paper proposes a novel way to transport ore from the moon to earth and shows the economics can work.

FULL TEXT

Acronyms

CNT	Carbon Nanotube
GDP	Gross Domestic Product
NEO	Near-Earth Object
PPP	Purchasing Power Parity
TEC	Total Energy Consumption

Problem Statement

In 1999 2.8 Billion people lived on less than $2 a day, while 1.2 Billion lived on over $50/day. The wide disparity comes largely from political factors which are beyond the scope of this study, but we can estimate the conditions necessary for achieving a reasonable standard of living (~ $30/day) for each world resident, and show the sustainable energy requirements necessary to meet that goal.

Technical Approach

First, we will show that individual standard of living can be roughly correlated with energy availability and consumption. Then we predict future sustainable energy requirements and show what materials will be in short supply. Finally, we introduce a future system that we enable us to acquire those minerals from the moon and show how the economics work.

Energy consumption affects our standard of living in several areas, the greatest affects are in residential power (heating/cooling and lighting), transportation (especially road), and industrial production. To prove this point we selected a basket of nine countries; three well-developed (USA, Germany, & Japan), three rapidly developing (China, India, & Indonesia), and three whose development has been slower (Mexico, Pakistan, & Venezuela). Figure 1 shows the total energy consumed by this basket of countries in 2001, and shows what percentage was consumed in each sector of their economy. The differences in which sector the energy was consumed will help correlate differences in standard of living later in the paper.

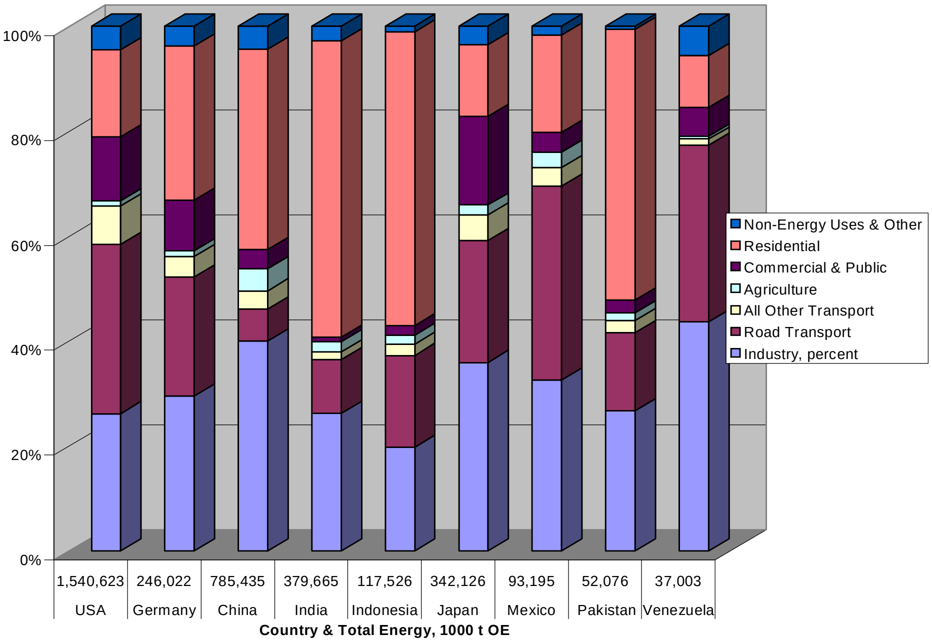

Figure 1: 2001 World Energy Consumption by Country by Sector.

Everything we eat and drink, the houses we live in, the cars we drive to work, and our jobs are produced using energy. Therefore, a direct correlation between Gross Domestic Product (GDP) and Total Energy Consumption (TEC) should be expected. The GDP we will use is adjusted for Purchasing Power Parity (PPP), which means the domestic products for each country has been priced to be equivalent to US prices so that the GDP can be compared to the US standard of living. GDP for our basket is shown in figure 2.

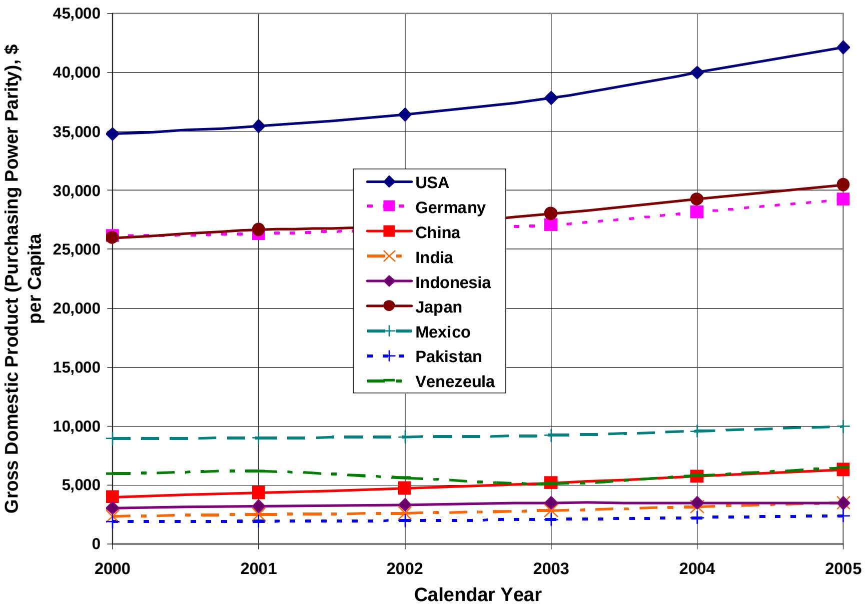

Figure 2: Gross Domestic Product per capita (using PPP) for Various Countries in 2000$.

Figure 2 shows a wide variance in GDP between the countries, which is reflected in turn in differences in the average standard of living (not shown). However, when we plot GDP per capita per barrel of oil energy equivalent consumed each year (figure 3), we see an interesting correlation between energy consumption and GDP.

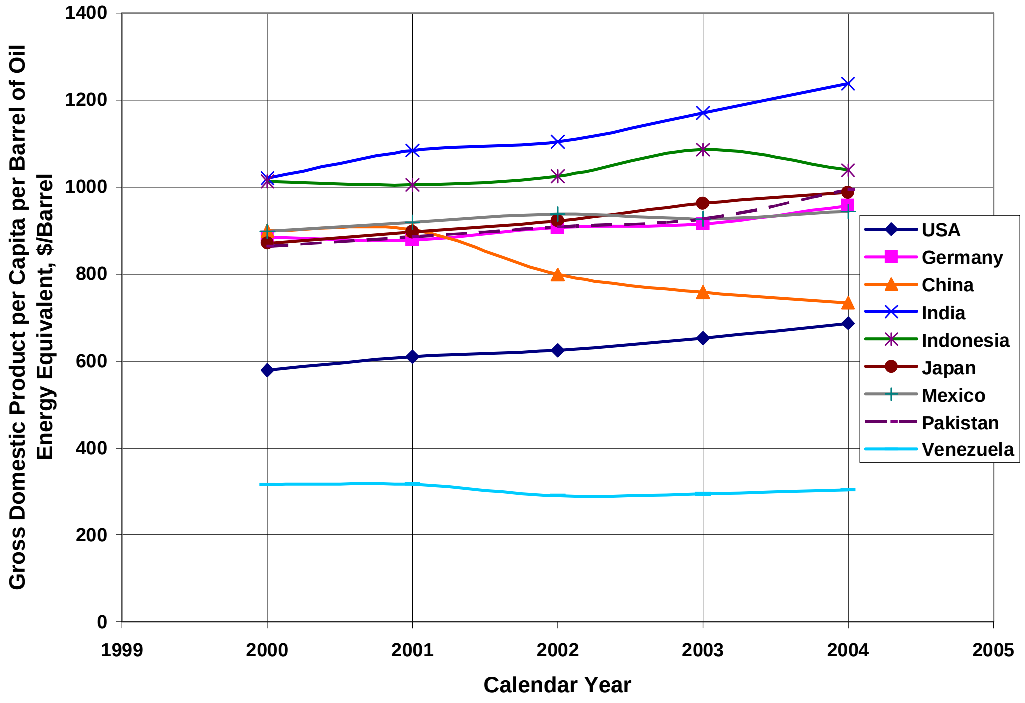

Figure 3: Gross Domestic Product (w/ Purchasing Power Parity) per capita per barrel of Oil Energy equivalent (Sources: BP 2005 Statistical Review & Economist Magazine Fact-book).

This data tells us that even though the GDP measured varies widely between highly developed and moderately developed countries, the amount of GDP generated per capita per barrel of oil energy equivalent consumed shows an average value across a wide spectrum of development levels. This value approaches $1000 of goods and services per barrel of oil energy equivalent in 2005, and increases in time roughly at 2% per year due to technology improvements. This fact can be used to predict the energy required to raise standards of living worldwide. The described universality of energy efficiency should not be surprising since the best industrial equipment and processes are shipped and licensed worldwide now that the cold war is over.

There are several outliers to this hypothesis. First, Venezuela which consumes most of its energy in the commercial and industry sectors, which has been impacted by the ongoing revolution where entire industries have been nationalized, and therefore huge drops in energy efficiency can be expected. The U.S. has had cheap oil for way too long and is not as efficient, especially in transportation sector, as most of the rest of the world, and needs to get its collective act together. China was on the curve until recently when its energy efficiency collapsed. We speculate that part of this is the tremendous program to build infrastructure both residential and public in preparation for the upcoming Olympic games (Infrastructure such as roads, dams, and stadiums don’t produce much additional GDP over time). Finally, we have highly efficient energy consumers like India and Indonesia who have a very efficient public transportation system and a surplus of manpower. They can substitute manpower for equipment in various industries like agriculture and construction, which increases the GDP for little increase in energy consumption.

The bottom line is that we propose that worldwide we should be able to generate a per capita GDP (based on PPP) of 1,000 $ (in 2000$) per Barrel of Oil Energy Equivalent consumed using technologies available in 2005 and increasing 2% per year afterwards. This supposition is key to our projections of future energy requirements, and shows where the world could be if political problems were overcome.

For instance, in 2004 worldwide energy production was roughly 75 billion barrels of oil energy equivalent (See Figure 4.).

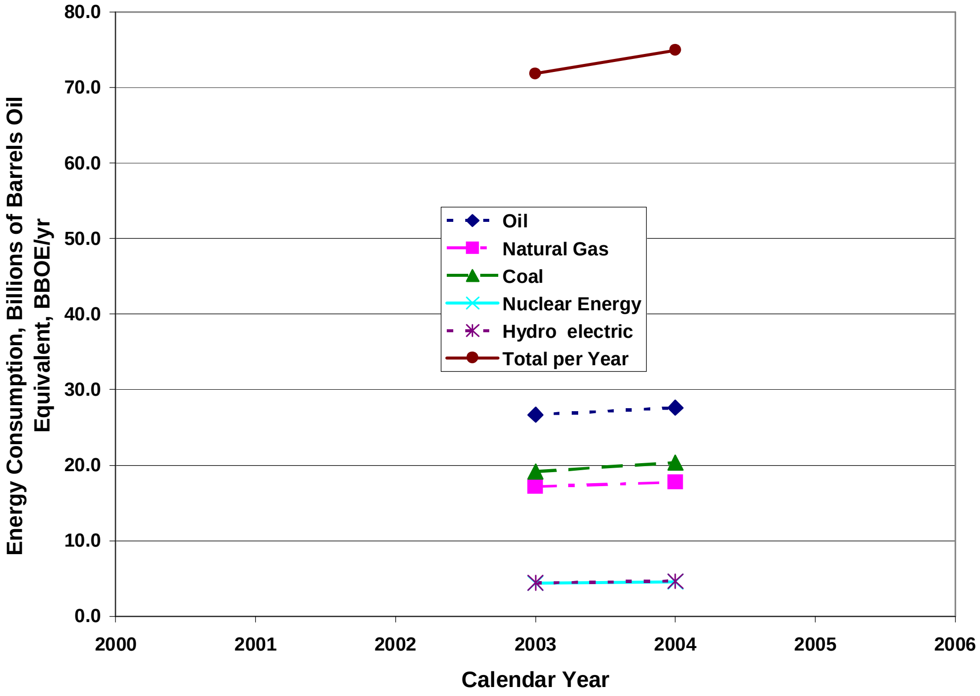

Figure 4: Worldwide Energy Consumption by Sectors (Renewables excluded).

Extrapolating energy consumption out to 80 BBOE in 2006, and applying our $1000 GDP per capita/ BOE, world energy production would support a GDP per capita of $12,120 (roughly equivalent to Mexico) for each of its 6.6 Billion inhabitants. The problem is that the infrastructure to utilize this energy is not available in many underdeveloped areas, and the most portable and heaviest used energy source (oil) is going to become much more expensive as it runs out, while the other major energy source (coal) is becoming environmentally untenable because of global warming. How do we replace 65% of our energy sources over the next few decades? On top of that, the world population is predicted to reach 9.2 Billion by 2055 which means we need an additional 30 BBOE (equivalent to the all-time peak world oil production) just to stay even with respect to GDP. We must start soon which means we must use existing technologies, and we need to focus on renewable sources because nuclear energy can help, but it remains politically divisive. For those who believe oil is abundant see figure 5, which shows that oil production peaks out at about 30 BBO/yr in 2010 and slowly drops as existing oil fields run out, and fewer new fields are discovered (oil is a finite resource).

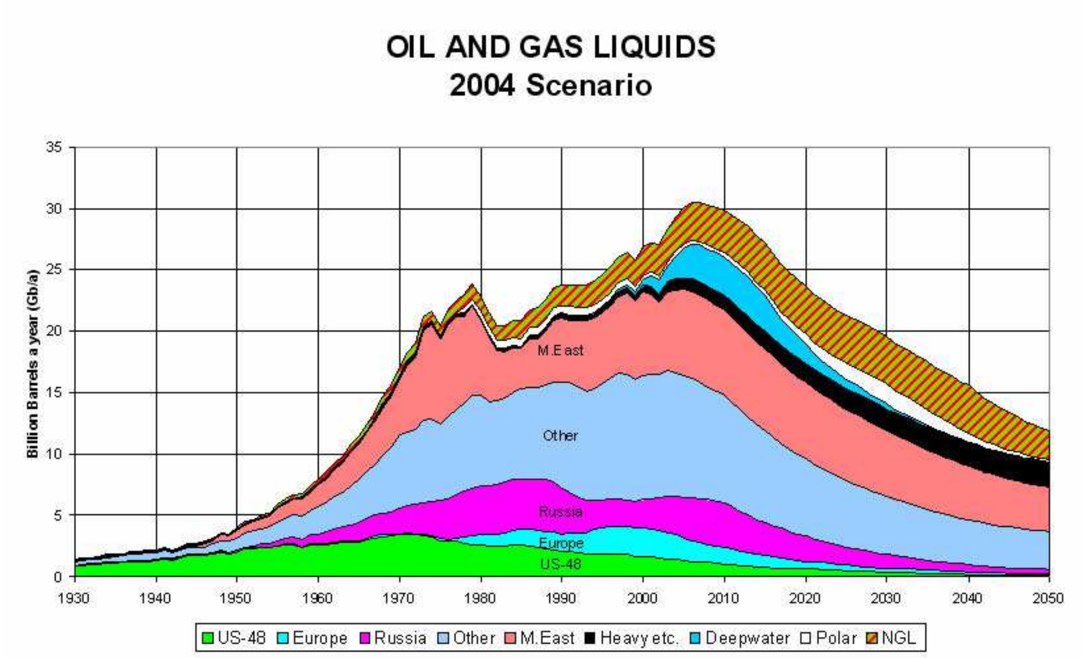

Figure 5: Historical and Projected World Oil Production data from Statistical Review of World Energy, Full Report Workbook 2004. BP Statistical Review website.

The Solution

Energy can be categorized by end-use. Road transport and agriculture consumed about 25% of the worlds total energy budget in 2002 and that number will probably increase over time as the population and the standard of living increase. Transportation and agriculture need a readily portable energy source. Consensus is leaning towards bio-diesel for trucks and tractors, and E-hybrids for automobiles, as the most satisfactory near-term solutions[1-5]. Electric cars and hydrogen fuel cells require technology breakthroughs which are not here yet, plus major infrastructure changes which may never be affordable. Bio-diesel and E-Hybrid technology is available and affordable today given the future price of oil.

For stationary power-plants multiple solutions are needed. For many parts of the world wind and solar power will be most efficient. The problem is and has been cost effective energy storage. Advanced rechargeable batteries are improving rapidly and could actually be moved from the generation site to use site in areas where an electric grid is lacking. For urban areas the most efficient solution is probably cogeneration using relatively small solid-oxide fuel cell units located in the industrial and commercial sites [6-8]. These fuel cells would run on natural gas or product gas in many industries and would generate direct power, plus high temperature exhaust gas which would be used to either generate additional power in turbines, or generate process heat for manufacturing. The turbine exhaust could then be used for area heating in commercial properties. The overall efficient of such a co-generation system reaches 75%.

As can be seen, a key ingredient to any shift to renewable energy sources is energy storage and this is the topic of the next section.

Energy Storage

Current large scale energy storage is pumped storage where water is pumped uphill into reservoirs during non-peak generating hours and flows back down through turbine-generators during peak power hours. This approach is capital intensive and will not work in many areas that lack abundant water. Batteries have been the standard for energy storage for many years, especially when mobility is important. Advanced Lithium-Ion batteries, rechargeable thousands of times, with specific energies near 200 kw-hr/kg are in test. Batteries this advanced can allow an E-Hybrid car to get 70mpg-80 mpg in town and 30 mpg-40 mpg on the highway. This significant improvement in fuel economy prolongs the oil supply and allows a rational transition to renewable fuels. The problem is, if we produced 25 million E-Hybrids a year (to replace half the world's oil-burning cars in twenty years), and each car carried 40 kw-hr of batteries, we would need roughly 400,000 tons of cobalt per year (eight times current yearly world production, and over twenty years we would require 50% of the total projected worlds supply of 15 million tons). Mining half the cobalt in the earth's crust seems extreme, which is one of the reasons we looked at space resources.

Space, The Final Frontier

Finding legitimate business opportunities is space has proven to be very difficult. The only money maker to date has been GEO Communication Satellites. (The LEO satellite phone business became profitable only after the development costs were written off through bankruptcy). With the President's announcement of a human return to the moon there is an opportunity to develop and use lunar resources for the betterment of mankind, but only if we're clever and design a transportation system which can deliver those resources for a few dollars per kilogram. This white paper addresses the issue of really low cost transportation between the earth and the moon.

Possible methods for transporting minerals from the moon's surface to Earth are the rail-gun, the rotary slinger, and the elevator. The rail-gun concept involves electromagnetically accelerating payloads from the moon's surface along rails and aiming them at the Earth (as in "The Moon is a Harsh Mistress"). The slinger concept uses a much simpler electric motor to build up angular momentum and "sling" payloads towards the Earth. Both of these concepts involve the use and recovery of payload buckets and some form of navigation system to correct for aiming errors. The elevator involves a long cable that payloads would travel up and out of the Moon's gravitational well. Because the payload stays attached to the cable until it is within Earth's gravitational well, navigation errors are much smaller and a smart navigation system and payload bucket are unnecessary.

It has been known for decades that it is possible to build an elevator from the lunar surface up through the earth-moon Lagrange points (L1 and L2) using existing high strength materials. Unfortunately, a very heavy counter-mass is needed because the moon rotates so slowly that an extra length of cable can't provide a centripetal balancing force as in the case of an earth space elevator. However, if a cable is extended from L1 down to moon's surface and at the same time three times it's length is extended from L1 down into earth's gravity well, the required counter-balance is only a few tens of tons (as opposed to several thousand tons if the counter-balance is close to L1). This configuration is shown in figure 6.

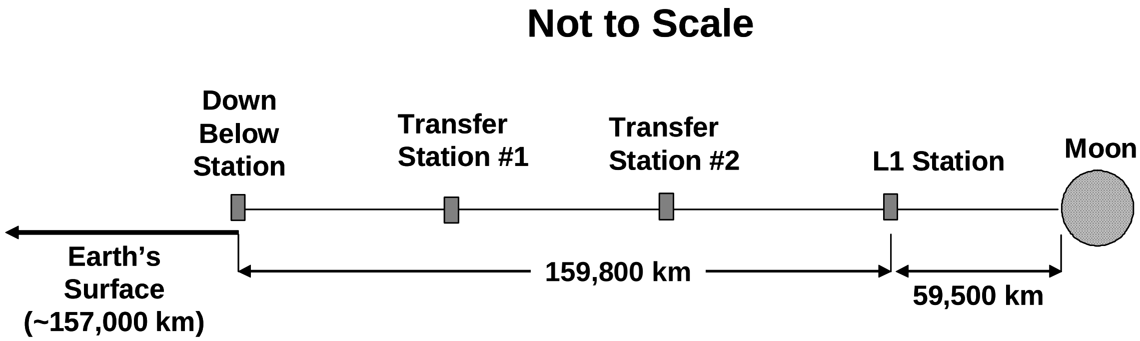

Figure 6: Proposed Lunar Conveyor Configuration.

The lowest station 157,000 km above the Earth's surface has several interesting properties. First, if the cable breaks the Down Below Station is in a stable 160 km by 157,000 km orbit (will not reenter and can be recovered at a later date). Second, if a thermally-protected object is dropped off with a fish-line tether or given a carefully timed 5m/sec push out of the Down Below Station it will enter the Earth's atmosphere 30 hrs later and can be recovered in various desert regions. Sintered regolith would be the thermal protection system and various metals are proposed as payloads. Third, it is possible to do a single burn out of LEO and rendezvous directly with the down below station. The spacecraft positions relative to the station versus time are shown in figure 7. The LEO-launched payload essentially comes to a complete stop relative to the station for about 30 seconds where it could be grappled and docked.

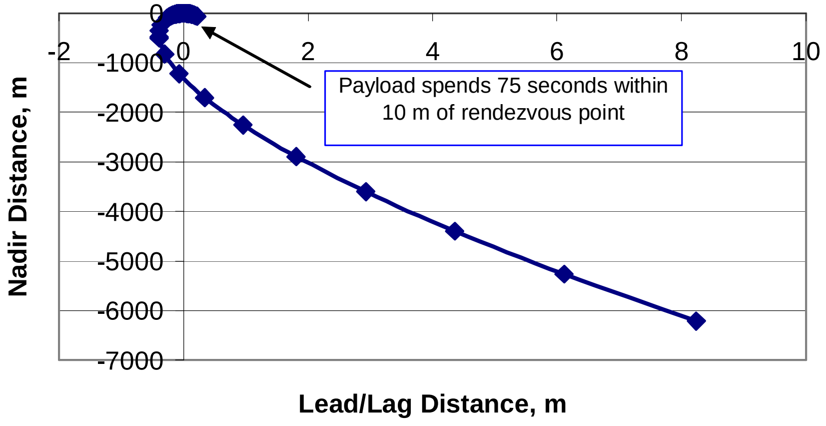

Figure 7: Transfer Orbit Approach to Down Below Station.

Economics

To make a reasonable economic case we need a viable market for lunar produced goods and a reasonable payback period for our investment. For safety, redundancy, and dynamic control we want multiple cables. It also needs high throughput so some cables will be for raising payloads from the lunar surface and others for returning empty buckets (and possibly imported goods). The mass of cable system is very dependant on cable technology and this is in transition with the introduction of carbon nanotube (CNT) fibers. The impact of CNTs on lunar conveyor mass is shown in figure 8. The masses shown are for one continuous cable length (~ 60,000 km) capable of supporting a five ton payload just above the lunar surface. The complete conveyor has six cables over each of four segments for a total of 24 cables. As shown, the goal is CNT cable with 30 GPa to 50 GPa strength. That cable will be available in one to five years depending on which projection is correct. Assuming 40 GPa is reached, then a spool with 60,000 km of "5 ton" cable could be launched to L1 using the launch vehicles and Orbit Transfer Vehicles (OTVs) developed by NASA for the Human Exploration Initiative (approximately 40 payload capability).

The entire conveyor assembly would require about 25 launches at $200 M each. Adding $3 B for development and production we can assume a net sunk cost of $8 B before payback can begin. For this cost, what throughput is required for a reasonable payback period? Assuming a conveyor speed of 100 km/hour and one ton payloads every 50 km along the conveyor we could deliver two tons per hour and 17,500 tons/year. To payback the conveyor cost in five years we must charge $8B/ (5 yrs* 17,500 tons/yr) = $91,430/ton or $91.43/kg. This assumption disregards the cost of money due to the relatively short payback period of 7 to 10 years depending on construction time, compared to the payback period of an oil pipeline which tends to be in the 20 to 30 year range.

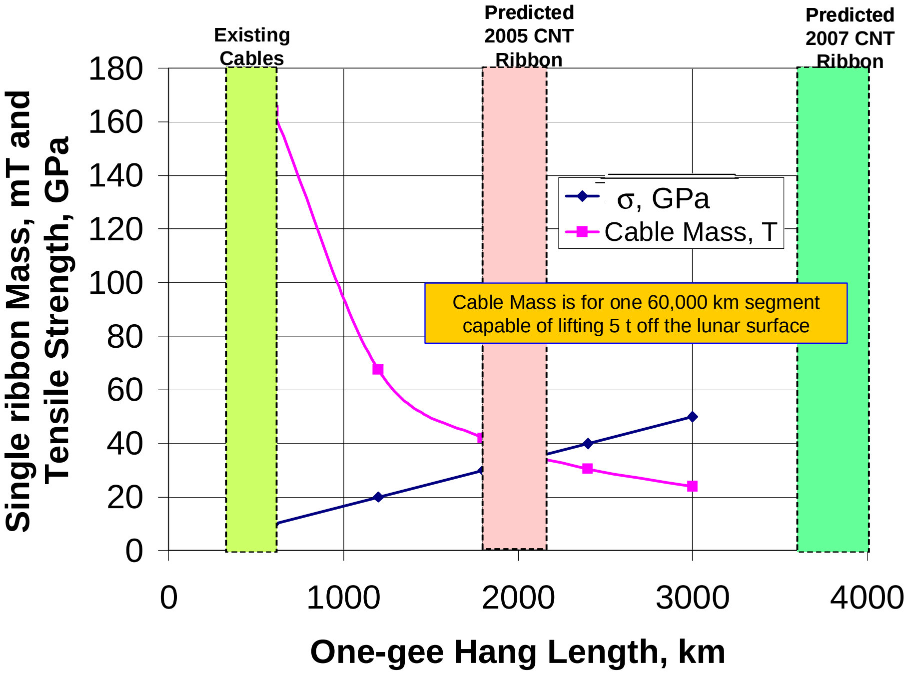

Figure 8: Elevator/Conveyor Cable Mass.

There are several materials that can be mined from the moon and will still be profitable after paying this freight charge. One is liquid oxygen delivered to LEO for rocket propellant. The cost of LOX in LEO delivered from the ground is about $2000/kg. Unfortunately this market is only a couple hundred tons per year, so it's only one percent of our throughput. The remainder would be "energy metals", like the platinum group, plus uranium, and thorium. The platinum group would be used for catalysts for fuel cells and other energy conversion devices and the uranium and thorium would be used for fuel in advanced fission reactors (fast breeder reactors which largely eliminate the radioactive waste problem by burning the long-lived products). Current prices for these metals run between $800/kg and $1000/kg and there is little chance of those prices falling in the foreseeable future. Hence, transportation costs are about 10% of the price, about the same as currently manufactured goods.

The issue then becomes the cost of mining and refining the "energy metals" on the moon. Fortunately, there appears to be a large concentration of thorium (and probably uranium) on the lunar near-side not far from the elevator terminus (see figure 9). This appears to be the results of a large nickel iron asteroid strike in antiquity (figure 10), and there is good chance other heavy metals could be found nearby in mineable quantities (on site assessment is required). The bottom line is that a valuable product, "energy metals," are probably available in quantity near the terminus of the proposed lunar conveyor, and if they can be mined and refined for about $300/kg there is roughly $7 B/yr in profit potential available to the mining concern, provided the lunar conveyor has been developed. Payback on the mining venture appears to be very rapid once the conveyor is in place, and transportation costs to the moon fall (one or two years). Hence, development of the lunar conveyor makes a valuable contribution to solving earth's energy problem and opens up the moon to further commercial development.

As a final note, the case for the development of the lunar conveyor rests on the assumption that scarce minerals such as cobalt will be required for efficient energy storage. There has been research lately into using more abundant minerals on Earth for energy storage but these technologies are yet to be proven. If these technologies do come to fruition, then the case for space will need to be revisited.

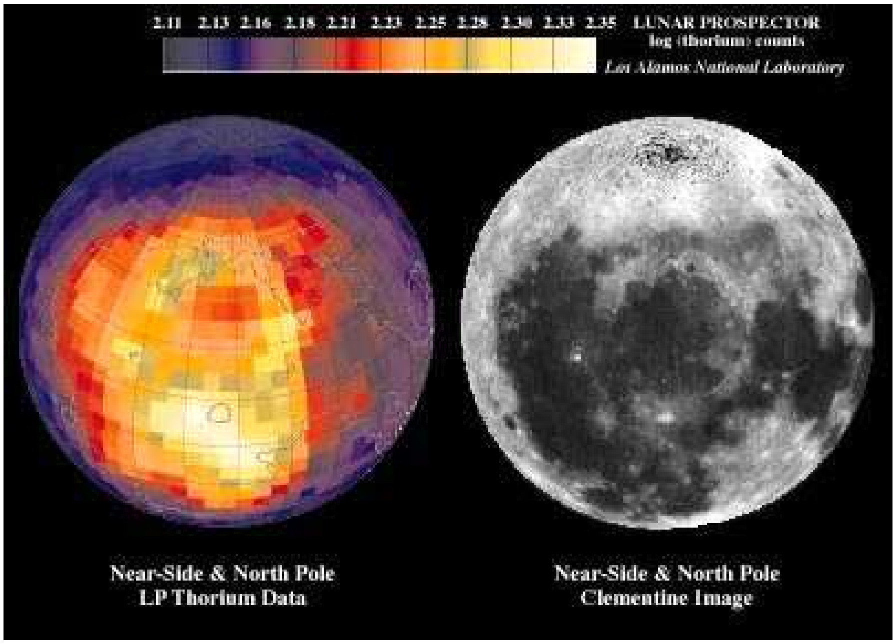

Figure 9: Clementine mapping on Nearside Thorium Deposits.

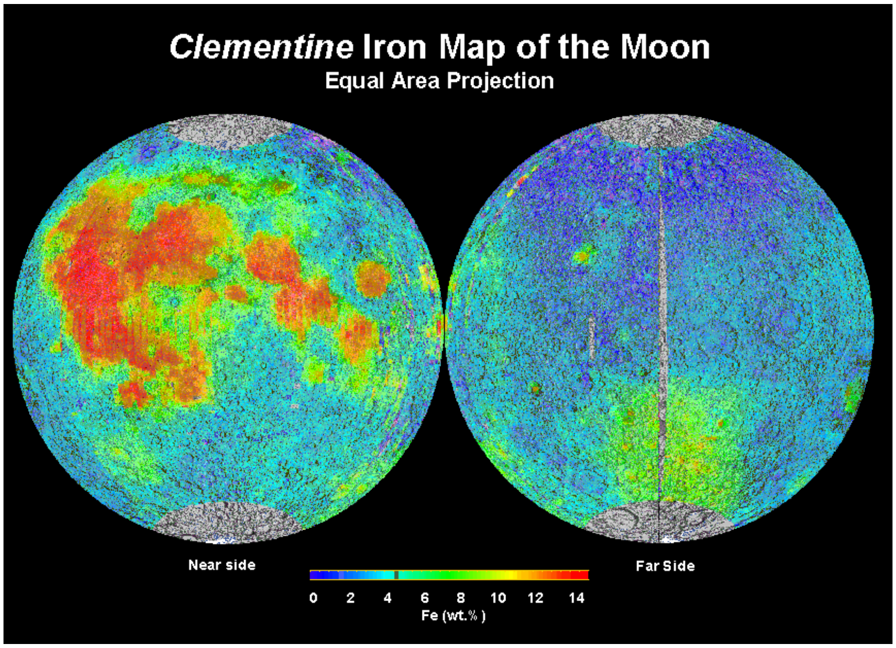

Figure 10: Clemetine-Mapped Lunar Iron Distribution.

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