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Capitalism with Zero Profit Rate?: Limits to Growth and the Law of the Tendency for the Rate of Profit to Fall

Minqi Li

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University of Utah
Department of Economics
1645 East Central Campus Dr., Rm. 308
Salt Lake City, UT 84112-9300
Tel: (801) 581-7481
Fax: (801) 585-5649
http://www.econ.utah.edu

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Minqi Li
University of Utah, Department of Economics
minqi.li@economics.utah.edu

1. Introduction

Capitalism is a socio-economic system that rests upon the endless pursuit of profit and capital accumulation. Its normal operations lead to as well as require the infinite growth of material production and consumption that are in turn based on the limitless exploitation of human labor and natural resources. However, after centuries of relentless capitalist accumulation, resources depletion and environmental crisis have reached the advanced stage.

The current global capitalist system depends on the abundant supply of non-renewable fossil fuels that provide for 80 percent of the world's energy supply. But now there is convincing evidence that the global production of oil and gas will soon reach the peak and start to decline thereafter. Further, to prevent or alleviate global warming with its potentially catastrophic consequences, it is necessary to phase out nearly all fossil fuels before the end of this century.

Mainstream environmental studies and environmental reformist movements have put their hope on renewable energies and improvement in energy efficiency.[1] However, this perspective has been subject to growing criticisms. A number of critics have conducted careful studies and find that it is highly unlikely that the renewable energies can meet the enormous and ever-growing demand for energy of global capitalism in a post-fossil fuels era and there are definite limits to the improvement of energy efficiency.

Without the ever-growing supply of energy and other resources, there is no way for capitalism to maintain limitless economic growth. To the extent the normal operations of capitalism necessarily result in as well as require growth and accumulation on

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[1] For example, see Lovins and Von Weisacher (1997), Hawken, Lovins, and Lovins (2000) and Brown (2003).

increasingly larger scales, the contradiction can only be resolved through a fundamental social change that replaces capitalism with an alternative social system that is compatible with the requirements of environmental sustainability.

The first part of this paper discusses the depletion of fossil fuels and the likely effects of various renewable energies and the nuclear energy on the future energy supply. The second part discusses the limits to improvement in energy efficiency. The third part discusses the depletion of other resources and the constraints imposed on economic growth. The fourth part relates the limits to growth to Marx's hypothesis on the "law of the tendency for the rate of profit to fall." It can be established that if the growth rate falls towards zero, then either the profit rate or the net investment has to fall towards zero. The last part concludes the paper, seeing the coming crisis as the expression of the conflict between the "productive forces" and the "existing relations of production" and discussing the historical constraints and possibilities for the post-capitalist society.

2. Limits to Growth: Energy Supply

Fossil Fuels and Global Warming

The current global capitalist economy depends on non-renewable resources for 87 percent of its total energy supply. Oil accounts for 34 percent of the worlds' total primary energy supplies, coal accounts for 25 percent, natural gas accounts for 21 percent, and nuclear energy accounts for 6.5 percent. Among the renewable energies, combustible renewables and waste (wood, other biomass, animal products, municipal waste, and industrial waste) account for 10.6 percent. These sources of energy are mainly used for burning that generates greenhouse gases and other air pollution. The environmentally preferable renewable energies are hydro, solar, wind, geothermal, tide, and wave. By far hydro electricity is the most important, accounting for 2.2 percent of the world's total primary energy supplies and all others account for a mere 0.4 percent. [2]

For advanced capitalist countries (OECD countries), oil accounts for 41 percent of the total primary energy supplies, natural gas accounts for 22 percent, coal accounts for 21 percent, nuclear energy accounts for 11 percent, combustible renewables and waste account for 3.4 percent, hydro electricity accounts for 2 percent, and all others account for 0.7 percent.

Therefore, oil and gas combined account for 55 percent of the global energy supply or 63 percent of the total energy supply of advanced capitalist countries. Oil and gas are non-renewable resources that will eventually be depleted. Now there is convincing evidence suggesting that global oil and gas production actually is likely to peak very soon, possibly within a decade, and start to decline thereafter.

According to Colin J. Campbell, global oil discovery peaked back in the mid-1960s. Since 1980, new discovery has been less than depletion for every year and the gap has tended to grow. Global conventional oil production was likely to have peaked in 2005. Unconventional oil sources (heavy oil, deepwater oil, polar oil, gas liquids) are unlikely to make a significant contribution. Global production of all oil liquids is expected to peak around 2010 and gas production is expected to peak around 2025. By 2050, the total production of oil and gas is expected to fall by about 40 percent from the peak level in 2010.[3]

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[2] The world energy statistics cited in this paper, unless stated otherwise, are from IEA (2006).

[3] Campbell conducted careful studies to "backdate" the official revisions of reserves in each oil field to their original date of discovery to get a true picture of the discovery pattern. For complete discussions of peak oil estimates, see Campbell (2005a and 2005b). For mathematical models that apply the Hubbert's method to the global situation, which correctly predicted peak oil production in US, see Korpela (2005). For popularized discussions of peak oil theories and the critiques, see Heinberg (2003 and 2004) and Kunstler (2005). The Association for the Study of Peak Oil and Gas Ireland (ASPO Ireland) publishes

Trainer (2006a) counts a total of 61 estimates of the world's total conventional oil resources and concludes that there is a considerable agreement on a figure under two trillion barrels (implying about one trillion barrels remaining since the world's total production so far has been about one trillion barrels). Campbell's current estimate is about 1.9 trillion barrels. The US Geological Survey put forward a very optimistic but widely citied figure of three trillion barrels that has been criticized by Campbell (2005c). Even if one accepts the US official estimate, it would only postpone the peak date of global oil production by about twenty years.

Coal is the other major source of energy global capitalism relies upon. Coal is relatively abundant. The world's current rate of production is approximately 5 billion tons a year. Assuming the total potentially recoverable coal being two trillion tons (cited from Trainer 2006a), the world's remaining coal could last 400 years.[4] Moreover, coal can be converted into oil and gas (though with some energy loss). However, if one assumes that to support world economic growth, coal production grows at an annual rate of 2 percent, it can only last 110 years. If one further assumes that coal production needs to grow more rapidly to replace the declining oil and gas so that the annual growth needs to be increased to perhaps 4 percent, then the world's total remaining coal can only last about 70 years. These estimates do not take into account that as production moves to increasingly more difficult fields, rising costs of production and declining energy return ratios could substantially reduce the amount of coal that is practically recoverable.

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monthly newsletters at www.peakoil.ie, which provides updated oil and gas production profiles and estimated dates of peak production.

[4] By comparison, the world's remaining recoverable conventional oil can last only about 40 years at the current rate of production, using Campbell's estimate, or 80 years using US Geological Survey's estimate.

The use of fossil fuels and other human activities release large and growing amounts of greenhouse gases that have contributed to global warming. Between 1973 and 2004, the world's total emissions of carbon dioxide (or CO_2, the main greenhouse gas) increased by about 70 percent, or at an annual rate of 1.7 percent. At the current growth rate, the world's total CO_2 emissions would rise to more than 200 percent of the current level by 2050 or nearly 500 percent by 2100.

The potentially catastrophic consequences arising from global warming have been widely discussed, including rising sea levels, flood, drought, heat waves, spread of human and crop diseases, decline of food production, and a possibility to trigger the next ice age. The Intergovernmental Panel on Climate Change estimates that to stabilize the concentration of CO_2 in the atmosphere at twice the pre-industrial level it is necessary to cut global annual CO_2 emissions to 8-12 billions tons by 2100. The current global emissions stand at about 27 billion tons. This suggests that the global CO_2 emissions and the use of fossil fuels need to be cut by at least 55-70 percent by the end of the century. However, to prevent catastrophes such a level of emissions could be too high. Even if we stop burning all fossil fuels immediately, the planet would continue to heat up for 150 years and oceans would continue to warm up for 1,000 years. Extreme reductions of greenhouse gas emissions may be required to prevent global warming from triggering a process of unstoppable chain reaction (Goldsmith 2005).

Both the reality of resources depletion and the necessity to prevent or moderate global warming suggest that the consumption of fossil fuels, on which the global capitalist economy depends for 80 percent of its energy supply, will have to be nearly completely phased out by the end of this century. To sustain unlimited economic growth, global capitalism would have to rely upon nuclear or renewable energies.

Nuclear Energy

The generation of nuclear electricity uses uranium (composed of two isotopes: U-235 and U-238) that is a non-renewable resource. The nuclear reactors under the current technology are burner reactors that use U-235 to generate enriched uranium. U-235 is not abundant, accounting for only 0.7 percent of the naturally occurring uranium. If the current technology is used, the world's total recoverable uranium would provide an energy supply that amounts to 150 billion tons of coal equivalent. Under the current rate of production, it could last 120 years. However, if nuclear energy is to be relied upon as the sole source of electricity production, the rate of production would have to be increased by six times and the remaining uranium can only last about 20 years.

A few countries (US, UK, France, Japan, and Russia) have experimented with breeder reactors that combine U-238 and U-235 to produce plutonium (which can be used to make nuclear weapons). Since the breeder reactor uses much less U-235, if successful it could increase the potential energy supply that can be derived from the world's uranium up to seven trillion tons of coal equivalent. Even such an enormous amount of energy will not allow the world economic growth to last very long. Suppose the world energy demand keeps growing at 2 percent a year using the remaining fossil fuels and suppose that by 2100, fossil fuels are completely phased out and the world energy demand is to be met by nuclear energy using breeder reactors. As the world's total energy demand by 2100 would be 6-7 times as much as today (or approximately 120-140 billion tons of coal equivalent a year), the world's remaining uranium could only support the world economy for about 50 years.

Nuclear energy of all kinds would cause serious environmental and safety problems. There is no good solution to the problem of nuclear wastes that have radioactive effects lasting thousands of years. Although there have been no major nuclear accidents since the Chernobyl accident in 1986, if nuclear energy is used on a very large scale over a long period of time, then some human failure will be inevitable, and any nuclear accident could lead to catastrophic consequences with long-lasting effects.

The breeder reactors have much more serious safety problems than the conventional reactors. Plutonium is regarded as the most poisonous material known on earth. With an accident, it could explode like an atomic bomb. Liquid sodium, the coolant used by breeder reactors, explodes on contact with air or water. Because of these problems, breeder reactors are expensive to build and maintain and are susceptible to long shutdowns. The French Superphenix reactor, the world's largest breeder reactor, operated for less than one year during its ten years of service. Currently only Russia continues to support the further development of breeder reactors.[5]

Nuclear fusion is the only proposed technology that theoretically has a chance to provide virtually limitless supply of energy. Nuclear fusion is the reaction that takes place in the sun and has been achieved by human beings in the form of hydrogen bombs. To use it for economic purposes, however, the reaction has to be controlled. To initiate a fusion reaction, temperature of more than 100 million degrees have to be reached and no known materials on earth are capable of containing such temperatures. So far scientists have attempted to confine the reaction through different processes. But each process requires more energy than the reaction itself generates and has succeeded in sustaining the reaction for no more than a fraction of a second.[6]

[5] On the prospect and limitations of nuclear energy, see Heinberg (2003: 132-139); Kunstler (2005: 140-146); Aroman and Cruzet (2005); and Trainer (2006a)

[6] There is another proposed nuclear fusion technology that uses lithium and is somewhat more promising. Lithium, however, is not very abundant. Trainer (2006a) suggests that it would yield only about as much energy as remains in fossil fuels (about 3 trillion tons of coal equivalent). This would make nuclear fusion using lithium a smaller contribution to possible future energy supply than breeder reactors. On nuclear fusion, see Craig, Vaughan, and Skinner (1996: 205-207) and Heinberg (2003: 157-160).

Wind and Solar

There are a variety of renewable energies, but wind, solar, and biomass are the three that are likely to make a significant contribution to the future energy supply.

Wind optimists claim that electricity derived from wind could be three to four times of present US electricity use. Trainer conducted a careful and detailed study and found that using reasonable assumptions of capacity, wind farm size, and exclusion factors (prior uses and distance from electricity grids), wind can meet no more than half of the present US electricity demand. In Australia, Trainer concluded that wind is unlikely to make a considerable contribution. A study by the Commission of the European Communities found that wind had a "realizable on shore technical potential" to meet about a quarter of Western Europe's electricity demand in 1990. A serious problem with wind is variability. In summer the output is likely to fall to only half the annual average. The average capacity utilization is no more than 25 percent. It takes large area of land and the capital cost is very high (Trainer 2005: Chapter 4).

Solar energy can be converted directly into electricity through photovoltaic cells. If photovoltaic plants are used to generate electricity, taking into account the need to store electricity in the form of hydrogen for the nighttime, the sunlight collecting area could be as large as 87 square kilometers for a plant that has a capacity of one thousand megawatts. The capital cost could be 130 billion Australian dollars or 47 times of the cost of an equivalent coal plant plus fuel for lifetime.[7] Photovoltaic cells can also be integrated into residential roofs. Trainer estimates that if all of the residential roofs are used, it may be able to meet 10 percent of Australia's current electricity demand (Trainer 2005: Chapter

[7] Trainer assumes an indeal site for Australia but for the winter season, with an average solar incidence of 4.25 kilowatt-hour per square meter per day. This is comparable to the average annual solar incidence for the US cited by McCluney (2005a).

2). McCluney estimates that if all of the solar energy falling on the US rooftops can be collected, it could meet about 80 percent of the current US energy demand (McCluney 2005a). This does not take into account the loss of energy due to conversion and some rooftops may be shaded. Suppose photovoltaic cells are installed on all of the US rooftops (with a total area of 18,000 square kilometers), the average solar incidence is 4.5 kilowatt-hour per square meter per day, and the average efficiency of photovoltaic cells is 10 percent (after taking into account variability in solar incidence and allowing for rooftops under less than ideal conditions), then the annual total production of electricity from this source could be up to 3 trillion kilowatt-hour or about 10 percent of the US present total primary energy supplies.[8]

Trainer (2005: Chapter 3) believes that the solar thermal system is probably the most promising solar electricity option.[9] The solar thermal system has advantage over the solar photovoltaic system in energy storage. Under the solar photovoltaic system, to deliver electricity in the nighttime, electricity generated in the daytime has to be stored in hydrogen, with an energy loss of 70 percent (the conversion from electricity to hydrogen results in about 30 percent loss of energy and the conversion from hydrogen to electricity results in about 60 percent loss of energy). By contrast, under the solar thermal system, heat collected in the daytime can be stored in oil, molten salt, or crushed rock, with an energy loss of less than 15 percent.

Suppose the average solar incidence is 8 kilowatt-hour per square meter per day (using the solar incidence in some good sites), and efficiency is 10 percent, then each square

[8] The average solar incidence and the total area of rooftops in the US are from McCluney (2005a). According to Trainer (2005: Chapter 2), using the current technology, the photovoltaic cells peak efficiency is about 13 percent.

[9] Trainer did not explain solar thermal electricity in detail. Based on the discussion of Craig, Vaughan, and Skinner (1996: 181-190), solar thermal electricity is about using certain devices to concentrate the solar rays that would generate heat, which could in turn be used to drive a conventional electricity generator (using steam to drive a turbine that generates electricity).

kilometer could receive enough solar energy to generate an amount of electricity that equals 23,897 tons of oil equivalent. The world's total land surface has an area of about 150 million square kilometers, about 17 percent of which is covered by deserts (Craig, Vaughan, and Skinner 1996: 428). If all of the world's deserts (25.5 million square kilometers) are used to generate solar thermal electricity, it could generate sufficient electricity to meet about 55 times of the present world energy demand.

In fact, obviously not all of the world's deserts can be used and the average solar incidence for the world's deserts could be far below what is suggested above. Like wind, solar thermal electricity also has a serious problem of variability. Trainer suggests that the winter output could be as low as 20 percent of the summer output. Significant seasonal difference would exist even in deserts close to the equator, such as in North Africa and West Asia. To build plants in these deserts would require very long transmission lines covering thousands of kilometers to meet the energy demand in Western and Northern Europe. The stable flow of electricity output that can actually be utilized is likely to be a fraction of the total annual electricity output.

Water is probably the greatest constraint on the large-scale application of the solar thermal system. Currently industry uses about 20 percent of the world's total water consumption. Within the industrial sector, the power plants, which use water to cool electricity generators, are among the largest users. In the US, the cooling of power plants accounts for nearly 40 percent of all industrial use of water (Brown 2003: 25; 128). Suppose for the solar thermal plants to generate an amount of electricity comparable to the world's current total electricity consumption (or about 11 percent of the world's present total primary energy supplies), it would need to use an amount of water that equals about one-third of the world's current industrial water consumption. Then to generate an amount of energy more than 50 times the world's present energy supply, it would take about 450 times of the world's current water consumption by the power generation industry, 150 times of the world's current water consumption by the industrial sector, or 30 times of the world's total current water consumption.

In the coming century, with global warming, shrinking rivers and lakes, depletion of aquifers, and spreading water pollution, even the current rate of water use would be unsustainable. The world would have to struggle to meet the demand for water by the agricultural and the residential sector (Brown 2003: 23-41). Where would the additional water come from? Even if somehow the desired amount of water is made available, how to deliver it into the desert?

Biomass, Hydrogen, and Liquid Fuels

Nuclear, wind, and solar energies can be used to generate electricity, which however cannot be directly used as liquid fuels. Electricity accounts for 16 percent of the world's total final consumption of energy. By contrast, liquid fuels account for about 25 percent of the world's total final consumption of energy.[10] Liquid fuels are indispensable inputs for modern transportation. They also play an indispensable role in powering heavy equipment in mining, construction, and agriculture (Heinberg 2003: 137; Kunstler 2005: 123-131; 145).

Biomass (from wood, corn, sugarcanes, and other plants) is the only renewable energy source that can be used to directly produce liquid fuels in the form of ethanol or methanol. The growth of biomass is subject to the natural limit on plant yields set by the process of photosynthesis. Under natural conditions, only about 0.07 percent of the solar energy received is stored within plant material as energy.

[10] This is estimated by the oil and gas used in the transportation sector and therefore has not included the liquid fuels used by the industrial and agricultural equipment.

Trainer (2005: Chapter 5) estimates that if all of Australia's present demand for oil and gas is to be met from biomass, it would take about four times all of Australia's cropland or twice all of the good forest area. To meet the US transportation demand for energy, it would take about five times the total US cropland or four times the total forest. The global potential biomass production might be able to meet about 20 percent of the world's current crude oil consumption.[11] All of these estimates do not take into account the fact that much of the land has already been committed and overused, and the biomass production potential could fall sharply without the energy subsidy from fossil fuels. The existing evidence therefore decisively rules out the possibility that the future world demand for liquid fuels can be met by biomass.

Electricity can be converted into hydrogen, which can be stored in fuel cells generating electricity to power cars and other vehicles.[12] The production of fuel cells uses scarce materials such as platinum. The large-scale use of fuel cells therefore may be limited by the availability of the scarce materials.

Trainer (1995: Chapter 6) argues that the physical nature of hydrogen largely rules out the possibility of a large-scale hydrogen economy. Hydrogen is very light. Very large volume of hydrogen is needed to carry a given amount of energy and it easily leaks through joints, valves, and seals. All of these make it very expensive to transport and store hydrogen and the overall energy returns end up being very low. A forty-ton truck is only able to carry an amount of hydrogen that is equivalent to less than 300 kilograms of petrol or less than 3 tons of petrol if hydrogen is liquefied (but there would be a large

[11] This is based on an assumption of an average productivity of ten tons per hectare over a total area of 600 million hectares. The world's total arable land is about 1,600 million hectares.

[12] There are electric cars can powered by batteries. But conventional batteries have to be recharged frequently and do not allow continuous long-distance traveling.

energy loss in liquefaction). The storage tank must be heavy and expensive and could weigh as much as 115 times of the hydrogen stored. Taking into account all of the energy losses that would incur in the conversion from electricity to hydrogen and then back into electricity, liquefying or pumping, transportation and storage, only 10-20 percent of the electricity generated ends up as useful energy for final consumption.

3. Limits to Growth: Energy Efficiency

It would be possible for economic growth to continue with constant or declining energy supply if energy efficiency keeps growing indefinitely. Energy efficiency is defined as the ratio of output over the inputs of energy. Output can be measured by GDP in constant dollars. The inputs of energy can be measured by standard energy units, such as oil equivalent or coal equivalent. Given the wasteful pattern of production and consumption of global capitalism, it is not surprising that there could be substantial scope for improvement in energy efficiency. However, in the long run, growth of energy efficiency is subject to certain definite and insurmountable limits.

The economy-wide energy efficiency depends on three factors: the ratio of final consumption to total production; the allocation of energy in different economic sectors; and the technical or engineering efficiency within each sector:

$$E = (F/Q) * \Sigma_{i = 1, \dots n}(w_i e_i)$$

Where E stands for overall energy efficiency, F stands for final consumption of energy, Q stands for total production of energy, w_i stands for the share of sector "i" in the final consumption of energy, and e_i stands for the technical or engineering energy efficiency within sector "i".

F/Q represents the ratio of final consumption to total production. Final consumption is typically substantially below total production because some energy has to be used for the production of energy and some energy is lost in the transformation of energy from one form into another and in the transmission of energy from the sites of production to the sites of consumption. In principle, energy efficiency can be improved if the above losses can be reduced.

The world's total final consumption of energy accounted for 69.1 percent of the total production in 2004. This actually represents a fall from the ratio of 76.3 percent in 1973. The ratio depends on technologies in energy production, transformation, and transmission as well as the physical and chemical properties of energy sources. The limits to technical efficiency in energy production and transformation sectors are in essence the same as the limits in other sectors and will be discussed later.

The physical and chemical properties of energy sources largely determine the energy return ratio (also known as energy returned on energy invested, the energy yield ratio, or the energy profit ratio), that is, how much energy would be produced with the input of one unit of energy. Oil is by far the most intense or the most efficient source of energy ever known. In the early stages of production, oil had an energy return ratio of over 100. One relatively recent study suggests that oil has an energy return ratio of 8-11, compared with 7-10 for natural gas, 10 for hydroelectricity, 4.5 for nuclear electricity, 2.5-9 for coal-fired electricity plant. The non-hydro renewable energies generally have very low energy return ratios. Wind electricity has an energy return ratio of about 2 and ethanol has a ratio of 0.7-1.8. The energy return ratio for solar photovoltaic electricity is somewhat controversial. But some suggest that if all of the energy expended in the building of plants and equipment as well as transportation is taken into account, the ratio could fall below one (that is, yielding negative net energy return).[13]

Over the past two centuries, the successive industrial revolutions have led to the transition from sources of energy with lower energy return ratios to sources with higher energy return ratios, first from traditional renewable energies (wood, wind, hydro-power, animals, human labor) to coal and then from coal to oil and gas. In the coming years, we are going to see this process being reversed. Increasingly, the sources with higher energy return ratios (oil, gas, and coal) will have to be replaced by the sources with lower energy return ratios (nuclear and renewable energies) and the energy return ratios for fossil fuels are likely to fall as depletion leads to rising costs of exploration and production. Therefore, without major breakthroughs in technical efficiency, the ratio of final consumption to total production is likely to fall in the future.

Now consider the second factor: the allocation of energy in different economic sectors. Statistically, the overall energy efficiency for the whole economy can be improved if energy is re-allocated from sectors with lower output per unit of energy to sectors with higher output per unit of energy. However, there are definite limits to such an approach of energy efficiency growth. First, at the extreme, if all of the energy is allocated to the sector with the highest output per unit of energy, this will exhaust all the possibility to improve efficiency through further re-allocation of energy. Secondly, the possibilities of energy re-allocation are limited by the technical complementarities and the limited possibilities of substitution between economic sectors. Suppose sector A has lower output per unit of energy and sector B has higher output per unit of energy, but sector A produces the inputs required for the production of sector B, or suppose both sector A and

[13] Statistics for energy return ratios are cited from Heinberg (2003: 152-153).

B produces final consumer goods but they cannot be substituted for each other, then energy input cannot be re-allocated from sector A to sector B. Thirdly, under capitalism, re-allocation of energy and other resources between sectors can take place only as a result of the process of profit rate equalization. Capital tends to move out of those sectors with lower profit rates and into those sectors with higher profit rates. There is no guarantee that the process of profit rate equalization would be consistent with what is required for the improvement of the economy-wide energy efficiency.

Industry accounts for 28 percent of the world's total final consumption of fossil fuels and electricity, transport accounts for 31 percent, other sectors (agriculture, commercial and public services, and residential) account for 30 percent, and non-energy use accounts for 11 percent. Suppose the economy can function perfectly well without industry and the overall level of output and consumption would stay unchanged without any energy input in the industrial sector, then at most the overall energy use can be reduced by 28 percent, and the energy efficiency may be improved by about 40 percent. This probably represents the limit to efficiency gains through re-allocation between sectors.

Finally, consider the potential for improvement in technical or engineering efficiency. All economic activities involve certain physical, chemical, or biological transformations and therefore must consume some energy. Given the nature of the transformations required by the economic activity, there is an absolute minimum amount of energy required by the laws of physics. For example, there is a minimum amount of energy that would be required to carry certain amount of weight over certain distance. No matter how much technology advances, the actual amount of energy consumed cannot fall below the minimum.

If all of the energy input directed towards a specific task is translated into useful "work" so that the amount of energy input is reduced to the theoretical minimum, then there is 100 percent of efficiency. In practice, some waste of energy is inevitable and the maximum attainable efficiency is likely to be far below 100 percent. This sets an insurmountable limit to progress in energy efficiency. Suppose an energy device has a technical efficiency of 40 percent, then no matter how much technology advances in the future, the total improvement in energy efficiency in the entire future can never exceed 125 percent of the current level of efficiency. [14]

Technology optimists claim that a "Factor Four" reduction in energy use is achievable without lowering living standards in advanced capitalist countries (Lovins and Von Weisacher 1997). Trainer (2006b) points out that most of their arguments and cases indicate 50-75 percent reductions and believes that a potential of 50 percent reduction is plausible. On the other hand, if fossil fuels are going to be largely replaced by nuclear and renewable energies, most likely the energy returns ratios will fall and could fall precipitously if hydrogen is used on a large scale to store electricity.

Table 1 presents the selected energy indicators of the world's major regions and economies. Among the world's large economies, Western Europe and Japan set the standard in term of energy efficiency. If the world as a whole can accomplish the same level of energy efficiency as Western Europe and Japan, then there is a potential for the world-wide energy efficiency to improve by about a third. To put the more optimistic claims in perspective, if a four-fold increase in energy efficiency is possible in advanced capitalist countries, then the OECD countries must manage to maintain the current level of economic activities with the per capita energy use of China or Latin America. For the

[14] On an introduction of the laws of thermodynamics and how they impose limits to improvement of energy efficiency, see Fisker (2005).

world as a whole, if a four-fold increase in energy efficiency is possible, then the world must manage to maintain its current level of economic activities with about two-third of the per capital energy use of Africa or South Asia.

The average energy intensity for the capitalist world-economy as a whole probably will never fall to what prevailed in pre-modern societies. There is no large-scale pre-modern economy left in today's world. However, the economic conditions of some low-income countries may be considered to be close to pre-modern conditions. In fact, Myanmar has the world's most "energy efficient" economy, with a GDP to energy use ratio about four times as high as the world average. Thus, a four-fold increase in energy efficiency probably represents the limit to what future improvement in energy efficiency can accomplish.

In the post-fossil fuels world, how much could be the sustainable level of world economic output? Suppose wind, solar photovoltaic, and solar thermal each can generate an amount of energy about 10 percent of the world's present energy supply (that is, assume each of them can generate about as much electricity as the world's current total electricity consumption). Suppose fossil fuels continue to provide an amount less than 20 percent of the world's present energy supply. Biomass and other renewable sources may provide 10-15 percent.[15] Thus, the above sources combined could approximately generate an amount about two-third of the world's present energy supply.

Given the enormous environmental and safety problems of the nuclear energy, it would be wise to use it as no more than an insignificant supplementary source of energy.

[15] The world's total technical exploitable capability of hydro electricity is estimated to be about 16,000 giga-watt hours (UNESCO 2006: 332-335). This is roughly comparable to the world's present electricity production. But the economically exploitable capability is likely to be far lower than that. Hydro electricity does cause certain environmental problems. The accumulation of silt behind dams could eventually render some major hydro electricity sites inoperable (Kunstler 2005: 119-121).

Further, the world's potentially recoverable uranium cannot last very long using the conventional burner reactors. However, if the world struggles to generate about as much energy as the present total energy supply, based on the above calculations, there would be a gap equaling about one-third of the world's present energy supply that has to be filled by nuclear energy. To fill this gap, the production of nuclear electricity would have to be increased by about five-fold. Most likely, this would have to be based on the very dangerous and problematic breeder reactors.

Using the more optimistic estimates, suppose energy efficiency can be improved by 100-300 percent, then the world economic output at most could rise to two to four times of the present level and there will be no more economic growth beyond this maximum. By comparison, if the world economy grows at its current rate of about 3 percent a year, then the world economic output should quadruple the present level by around 2050 and reach about 16 times of the present level by around 2100.

The above discussions have not taken into account the limitations that may arise from the high financial costs of nuclear and renewable energies. The failed French Superphenix breeder reactor (with a capacity of 1,200 megawatts) was reported to have cost 7.7 billion Euros during 1986-1996 before it was taken out of service (Aroman and Cruzet 2005). By comparison, Trainer (2006b) reports that a coal plant (with a capacity of 1,000 megawatts) plus fuel for lifetime cost 3.7 billion Australian dollars.[16] Comparison would be sensitive to time and exchange rates used. But a rough comparison (assuming 1 Euro = 1.7 Australian dollars) would suggest a breeder reactor would cost at least 3 times as much as a coal plant. Trainer (2006b) also estimates that the capital cost of wind

[16] Trainer (2005) earlier suggested that the cost for a coal plant with the same capacity plus fuel for lifetime would be 2.8 billion Australian dollars.

electricity and solar thermal electricity would respectively be three times and six times as expensive as coal plant plus fuel over lifetime.

The modern transportation depends on the abundant and ready supply of liquid fuels. As is discussed above, there is no real good solution to the problem of liquid fuels in the post-fossil fuels world. If this problem cannot be effectively addressed, then the nature of the world transportation would have to be fundamentally transformed and its volume would have to be cut drastically.

The inter-continental transportation over sea and air would largely disappear. With the exception of some remaining ships and airplanes powered by the dwindling supply of fossil fuels, inter-continental transportation would by and large return to the pre-19th century conditions.[17] The current system of global economic division of labor would collapse as a result.

Electrified railways could experience a great revival and play an important role in intra-continental long-distance transportation. Intra-city transportation would be dominated by public transportation, electric cars, as well as various pre-modern vehicles. But overall transportation is likely to be much more expensive given the expensive electricity generated by nuclear and renewable energies.

Thus, even if aggregate energy supply may be adequate to support a level of output two to four times as the present, the inadequate supply of liquid fuels could become an insurmountable bottleneck. Few nation or region is able to meet its own demand for most (not to say all) of the resources required to run a modern economy from domestic supply.

[17] Some ships may be powered by nuclear reactors installed on board. But that probably would be very expensive and not economical for civilian purposes.

With the inter-continental commercial transportation largely disappearing and intra-continental transportation becoming much more expensive, production and consumption would have to largely depend on the availability of local resources and in effect be bound by the least abundant resources. This would almost certainly lead to a dramatic cut of global production and consumption.

4. Limits to Growth: Other Resources

A global capitalist economy that pursues limitless growth and accumulation demands not only ever-growing supply of energy but also ever-growing supply of many other resources, such as mineral resources, water, timber, and food.

Mineral Resources

Mineral resources are essential inputs for modern industry and construction. The nonmetallic minerals are considered to be generally abundant. There are only six metals (silicon, aluminum, iron, magnesium, titanium, and manganese) considered as "abundant metals," individually making up at least 0.1 percent of the Earth's crust by weight. All the other metals are geo-chemically scarce metals. Between 99.9 and 99.99 percent of the total amount of any given scarce metal is distributed in common rocks and only a tiny fraction occurs in ore minerals. It takes ten to one hundred times as much energy to recover metals from the richest common rocks as to recover from the lowest grade of ore deposits. Therefore, only ore deposits may be economically exploited (Craig, Vaughan, and Skinner 1996: 209-298; Trainer 2006a).

Table 2 lists the current rates of production, the reserve base (including current reserves and probably recoverable resources), and the resources (including all potentially recoverable resources) for the world's 32 basic metals. At the current rates of production, all the probably recoverable resources for 14 out of the 32 basic metals would be exhausted in less than 100 years. If the world's resources consumption keeps growing at 2 percent a year, then all the probably recoverable resources for 25 basic metals would be exhausted in less than 100 years and all the potentially recoverable resources for 17 basic metals would be exhausted in less than 150 years.[18]

The production of energy using renewable and nuclear sources presupposes the existence of a modern industrial and construction sector that is capable of producing the required capital structures and equipment. However, without the abundant supply of a wide variety of metallic minerals, the post-fossil fuels world may not have the capacity to produce the required structures and equipment and its ability to produce energy from renewable and nuclear sources would therefore be limited.

Energy, Water, and Food

Agriculture is the basis of all human civilizations. Rural population still accounts for about 51 percent of the world population. But agriculture accounts for only 4 percent of the world GDP and in OECD countries, agricultural employment has fallen to only 4 percent of the total labor force.[19] These numbers do not give a fair representation of the importance of agriculture to our world.

Modern agriculture is extremely energy and water intensive, and therefore is fundamentally unsustainable. To produce one calorie of food, it took a tiny amount of fossil energy (less than 0.1 calorie) under the traditional Asian agriculture. As late as in 1910, the US agriculture still managed a one-to-one energy return ratio from fossil fuels

[18] Trainer (2006a) suggests that if the world population grows to 10 billion and the 10 billion people use the minerals at the present rich world per capita rates, one third of the 36 basic minerals (in term of potentially recoverable resources, defined as 10 percent of the minerals within the top 4.6 kilometer depth of the earth's crust) would have been completely exhausted in about 35 years.

[19] The Economist, *Pocket World in Figures*, 2007 Edition, p. 244.

to food. Under the contemporary modern agriculture, it takes ten calories of fossil fuels to produce just one calorie of food (McCluney 2005a).

Modern agriculture depends on oil and gas for the production of chemical fertilizers and pesticides, operation of farm machineries, packaging, and transportation of agricultural produces. Even with the enormous subsidy of fossil fuels, modern agriculture has already been suffering from diminishing returns. Soil erosion has undermined the effectiveness of fertilizers. Insects have developed generic resistance to pesticides. There are signs that the global food production may peak in the near future (Goldsmith 2005; Heinberg 2003: 21).

Figure 1 presents the world's total and per capita grain production. The world's per capita grain production peaked in 1984. The total grain production has continued to grow but the growth rate has fallen since the 1960s.[20]

Water is another essential input for agriculture. Modern agriculture depends on large-scale, perennial irrigation to maintain high productivity. Worldwide, the amount of water for agricultural irrigation is doubling every 20 years and consumes nearly 70 percent of all the water used. About 11 percent of the world's cropland is under perennial irrigation and supplies 40 percent of the world's food. The worldwide depletion of aquifers now amounts to 160 billion cubic meters a year. If the world's main aquifers are completely depleted, world food production would fall precipitously. The world's main rivers provide another major source of water for agriculture. But with global warming and glaciers retreating, the flow of rivers can be reduced by up to 25 percent. Modern

[20] Data for the world's grain production are from Earth Policy Institute (2006).

irrigation has also led to waterlogging and salinization, reducing the area of productive land available (Goldsmith 2005; Kunstler 2005: 157-161).

Without the abundant supply of fossil fuels and once it becomes no longer possible to over-extract the aquifers, the world food production would almost certainly fall substantially below the current level. Given that the world population is likely to increase from the current 6 billion to between 8 and 9 billion by 2050, there would be a very serious world food shortage. The geopolitical conflicts and chaos that are likely to follow could lead to catastrophic consequences beyond imagination.

In the long run, the sustainable level of world food production and population will be much lower than the current level. Some suggest that the world population may need to fall to 2 to 3 billion to be sustainable (McCluney 2005b).

In the post-fossil fuels world agriculture has to become much more labor intensive and labor productivity would have to fall accordingly. The enormous growth of labor productivity in the agricultural sector has allowed the massive transfer of labor force from agriculture to industry and services over the past two centuries. Without the technological revolution in the agricultural sector there would have been no industrialization and the so-called "services economy". If the labor productivity in the agricultural sector returns more or less to the pre-modern levels, then the share of rural population and agricultural labor force must rise to 80-90 percent of the total population and labor force. Such a transfer of labor force implies a fall of the world non-agricultural output by 60-80 percent (and 80-90 percent for advanced capitalist countries). As nearly all of the value of output now derives from the non-agricultural sectors, the economy-wide productivity as a result must fall by 60-80 percent.

The above discussions suggest that agriculture could prove to be the weakest link in the post-fossil fuels world. When the resources constraints on agriculture are taken into account, the long-term sustainable world economic output could fall to less than one quarter of the current level (and the per capita output less than half).

5. Zero Growth and the Law of the Tendency for the Rate of Profit to Fall

Therefore, at best, the world economy may grow to several times of the present level and then stabilize. There will be no more economic growth afterwards. The potentially attainable level of output would be substantially lower if one takes into account the constraints of liquid fuels and mineral resources. At worst, the world economy and population would have to fall to a fraction of the current levels. The humanity is confronted with the most difficult challenge of how to complete the transition from the current unsustainable levels of output and population to the future sustainable levels while making effort to avoid or at least alleviate the nearly inevitable ecological and human catastrophes.

In any case, for the post-fossil fuels (or the post catastrophe) society to be viable, it must rest upon sustainable relations with the environment, which would in turn require a stable and reasonable flow of material production and consumption that is sufficient to meet the populations' basic needs. In other words, it has to be a society of zero growth. What would be the implications for capitalism of all of these? Can a zero growth society be compatible with an economic system based on the pursuit of profit and accumulation? To address these questions, it would be useful (and interesting) to revisit the traditional Marxist debate on the "law of the tendency for the rate of profit to fall."

In *Capital* (volume 3) Marx advanced the famous hypothesis: "the law of the tendency for the rate of profit to fall." Marx argued that capitalist technological progress tends to be characterized by rising organic composition of capital (that is, falling output-capital ratio), which in turn leads to falling rate of profit. As capitalism is an economic system based on the pursuit of profit and accumulation, in the long run, the fall of the profit rate would undermine the foundation of capitalism and contribute to its final demise (Marx 1967[1894]: 211-266).

Marx recognized that there are various "counteracting influences", the most important of which is the "cheapening of elements of constant capital." However, Marx believed that in the long run, these counteracting tendencies are not strong enough to prevent the "law" from asserting itself. The validity of the "law" has been intensely debated by Marxists. The empirical evidence has been mixed.[21] The rest of this section discusses what are the implications for Marx's hypothesis if the world economy is moving towards permanent zero growth (and possibly negative growth) in the coming century.

The profit rate equals the product of the profit share and the output-capital ratio. In the long run, given certain profit share, the profit rate depends on the value of the output-capital ratio:

$$\mathrm{Lim}_{t\to\infty}R = (\Pi/Y) * \mathrm{Lim}_{t\to\infty}(Y/K) \qquad (1)$$

Where R is the profit rate, Π/Y is the profit share in the output, and Y/K is the output-capital ratio. Moreover, it can be shown that in the long run, the output-capital ratio

[21] For earlier studies on the trend of the output-capital ratio and the profit rate in the US economy in the post-WWII period, see Moseley (1991 and 1997) and Shaikh and Tonak (1994). Dumenil and Levy (1993 and 2004) studied the long-term movement of the output-capital ratio and the profit rate in the US economy between 1869 and the late 20th century and found that during two historical phases (between the 1870s and the 1890s and between the 1940s and the 1970s) both the output-capital ratio and the profit rate tended to fall. However, over the entire period the output-capital ratio and the profit rate fluctuated around essentially constant trends. A recent study by Li, Xiao, and Zhu (2006) finds that there has been a strong tendency for the output-capital ratio to fall in Japan and the long-term trend for the output-capital ratio in UK has been slightly downward.

depends on the marginal output-capital ratio, that is, the ratio of the change in output over the change in capital stock:

$$\mathrm{Lim}_{t\to\infty}(Y/K) = \Delta Y/\Delta K \qquad (2)$$

To see why equation (2) holds, consider that if $\Delta Y/\Delta K > Y/K$, the output-capital ratio would tend to rise until $\Delta Y/\Delta K = Y/K$. Similarly, if $\Delta Y/\Delta K < Y/K$, the output-capital ratio would tend to fall until $\Delta Y/\Delta K = Y/K$. From (1) and (2), the following can be derived:

$$\mathrm{Lim}_{t\to\infty}R = (\Pi/Y) * (\Delta Y/\Delta K) = (\Delta Y/Y) / (\Delta K/\Pi) \qquad (3)$$

Therefore, in the long run, the profit rate depends on the economic growth rate ($\Delta Y/Y$) and the share of net investment in profit ($\Delta K/\Pi$), which may be referred to as the net investment share.

There are two possible scenarios under which the profit rate would tend to fall in the long run. First, holding the economic growth rate constant, the net investment share tends to rise (or the net investment share rises faster than the economic growth rate). Under capitalism, individual capitalists and capitalist nation states are in constant competition with each other. To survive competition and to enrich themselves, capitalist corporations, states, and small businesses must engage in capital accumulation to expand the scales of production and to increase productivity. Therefore, normally a portion of the profit should be committed to net investment.

However, there is no particular reason why the net investment share should keep rising. In the first place, the net investment share can never be greater than one. There are, moreover, limits to the increase of net investment share. The capitalists have to pay taxes to the state and some of the capitalist profit has to be used for capitalist consumption.

Second, holding the net investment share constant, the economic growth rate tends to fall (or the economic growth rate falls faster than the net investment share). Empirically, until now there has not been a long-term tendency for the growth rate of the global capitalist economy to fall. As a result, until now there has not yet been strong empirical evidence in support of Marx's hypothesis.

However, after centuries of limitless accumulation and growth, the global capitalist economy has expanded to the point that the underlying material foundation (the earth's resources and the ecological system) for accumulation has been largely undermined by accumulation itself. If the analysis presented in this paper turns out to be largely correct, then the world economy will stop growing and possibly enter into a period of prolonged contraction at some point after the mid-21st century. That is, the world economic growth rate would fall towards zero and possibly become negative.

What would happen to the profit rate? Given positive net investment share, zero or negative economic growth rate implies that the profit rate would have to fall towards zero. This would confirm the "law of the tendency for the rate of profit to fall" (though under a very different context).

Can capitalism survive with zero profit rate? Ironically, the scenario of zero profit rate would be consistent with the "golden rule steady state" in the neoclassical Solowian model where the marginal product of capital equals the rate of depreciation and consumption is maximized. But if the profit rate does fall to zero, then what's the point of being a capitalist?

What could be the "counteracting influences" to such a scenario? If the economic growth rate falls towards zero, then the profit rate will not fall towards zero if and only if the net investment share falls towards zero or become negative.[22]

It is not clear how the net investment could ever fall towards zero so long as the profit is positive and the capitalist system functions normally. Capital accumulation could bring about more profit in the future and those who do not engage in capital accumulation risk losing their status as capitalists. Therefore, under normal conditions, it seems always "rational" for individual capitalists to use a portion of their profit for the purpose of accumulation. One might say that the capitalist class as a whole faces an insoluble "prisoners' dilemma."

It is conceivable that as the profit rate falls, the net investment share would also tend to fall. However, given the unstable nature of the capitalist economy, instead of leading to a stable state with zero net investment, the fall of the profit rate could lead to a general collapse of the investors' confidence. In that case, the net investment share could become negative, that is, the investment level would fall below what is required to replace the depreciation of capital. Not only there would be no more capital accumulation, but capitalism would also fail to maintain simple reproduction.

Hypothetically, if the net investment does fall to and manages to stabilize at zero, it means the entire capitalist profit is absorbed by capitalist consumption. In other words, the profit completely degenerates into the rent, and the capitalist class completely degenerates into a parasitical exploiter class. Can such a purely parasitical capitalism be

[22] Note that in equation (3) the long run equilibrium profit rate does not depend on the profit share so long as both ΔY and ΔK are positive.

politically and socially viable? No exploiter class could ever exist and rule the society if it does not play certain objective social function. The prosperity of the Egyptian and the Chinese empires depended on their effective management of the large-scale water works on the Nile and the Yellow River. The rule of the Catholic Church depended on its monopoly over education and knowledge in the medieval Europe. For capitalism, "development of the productive forces of social labour is the historical task and justification of capital." (Marx, 1967[1894]: 259)

The word "justification" is not used in the moral sense. The basic argument is that no social system can exist and be stable for a long period of time simply based on repression or deception. To be "sustainable", a ruling class has to play certain indispensable function required by the mode of material production at the time. From this perspective, the capitalist class has played a historically useful role through its unique tendency to use surplus product for the purpose of capital accumulation, thus having contributed to the development of productive forces. Once it becomes a purely parasitical class (and therefore becomes "dispensable") there would be nothing that can prevent the exploited great majority from rising up.

One might argue that even a static capitalism could still be justified on the ground it is more "efficient" than any alternative social system. This immediately raises the question how efficiency is defined and measured. Presumably, a non-capitalist society defines and measures it rather differently from a capitalist society. Even if one accepts the capitalist criteria of efficiency, it is not clear capitalism is necessarily more efficient than other social systems.

The theoretical case for the efficiency of capitalism largely rests upon the neoclassical ideal of perfect competition. In reality, capitalist markets are flawed in many ways (monopolies, externalities, public goods, asymmetric information, moral hazards, etc.). At the macro-level, capitalist economies are characterized by enormous wastes (unemployment, idle production capacity, advertisements, and artificial obsolescence). If all inputs (such as intensity of labor) and costs (human and environmental costs) are measured correctly, it is not obvious at all that capitalism is more efficient than non-capitalist systems that have historically existed or could conceivably exist in the future.

A stronger case can be made for capitalism regarding its constant drive towards technical innovation. But under capitalism, technical innovation is inseparable from capital accumulation. Both are driven by the pursuit of profit and the pressure of competition. If the net investment has fallen to zero, then presumably either the competitive pressure or the profit motive or both have become so weak that they could no longer motivate capital accumulation. What would be the unique capitalist motivation for technical innovation then?

In any case, without growth (and therefore the promise and the prospect of better life in the future), why would the exploited great majority continue to tolerate all of the social ills of capitalism, such as inequality, poverty, unemployment, slavery-like working conditions in much of the world, and other failures in meeting basic social needs (health care, education, care of children and old people)?

All of these, however, could prove to be purely academic and unnecessary speculations. It is quite possible that the capitalist system will not be able to survive the coming great crisis and will never reach the "steady state".

6. The Endless History

For Marx, all social systems are historical in the sense that every social system can exist only under certain historical conditions (certain level of development of "productive forces"), but as the underlying historical conditions inevitably tend to change (the "productive forces" tend to develop), sooner or later a point would be reached when the existing social system becomes no longer historically viable (the "existing relations of production" become "fetters" of development of the "productive forces") and has to be replaced by a new social system that is appropriate for the new historical conditions.

The "productive forces" have to do with how human beings interact with the nature to produce and reproduce their material conditions of life. Under certain conditions, human beings may transform the nature to enhance the ability to meet their own needs. The transformation, however, can only take place within the limits of physical and ecological laws.

Capitalism, through its pursuit of endless accumulation and growth, has fundamentally transformed the relationship between the human beings and the nature. The human activities of material production and consumption have expanded to the point that the very existence of human civilization is at stake. There cannot be a more acute expression of the conflict between the "productive forces" and the "existing relations of production," and the conflict can only be resolved by rejecting the existing socio-economic system (assuming the humanity will survive the coming crisis).

It is not the purpose of this paper to elaborate on the possible forms of post-capitalist societies. However, some broad historical constraints and possibilities may be outlined. The post-capitalist society must manage to meet the population's basic needs in ways that are compatible with ecological sustainability. This suggests that market relations must not play a dominant role in allocating goods, services, and resources because the dominance of market relations (even under conditions of simple commodity production or "market socialism" where the owners of the means of production are the workers, or the state, or various "collectives") would inevitably force the economic players (individuals, businesses, and states) to engage in relentless competition against one another and as a result pursue profit-making and capital accumulation. The economy, therefore, must be re-organized to be based on the production for use value or basic needs. In other words, it has to be some form of planned economy.[23]

More importantly, there is the question whether the post-capitalist society would be a classless society where people are freed from all forms of exploitation and oppression (that is, communism). There is a distinct possibility that the enormous difficulties that the humanity has to go through in the transition from capitalism to post-capitalism could lead to a return to some form of pre-capitalism.

On the other hand, capitalism will leave us with some positive legacies. Much of the world's labor force has been transformed into proletarianized workers. The world's exploited classes are much better educated than their predecessors. It is widely accepted by the world's population that a legitimate government must govern through some form of democracy and some imperfect democratic political institutions have been established in much of the world. The world's exploited classes have been influenced by various Marxist and socialist ideas and have been under different degrees of political and economic organization. The collective political strength and potential of the world's exploited is probably stronger than any previous exploited classes at comparable historical moments.

[23] Of course, the planning may be centralized or decentralized (with local communities being the planners) and the planning process may be democratic, undemocratic, or bureaucratic but subject to some democratic checks. It can be debated whether market relations should continue to play an insignificant role in the economy. I personally do not consider market relations to be indispensable for delivering high quality of life in the post-capitalist society.

Unlike in pre-capitalist societies, it is unlikely for the post-capitalist rulers to justify their rule on religious grounds (though this cannot be completely ruled out). Moreover, the requirements of ecological sustainability would deprive them of the justification of growth. In this context, could any ruling class manage to rule without at least pretending to rule for the benefit of society as a whole?

Despite all of the resources constraints discussed above, a substantial part of the technology and knowledge developed in the capitalist era may be preserved. It is possible that the post-capitalist society can have a level of labor productivity substantially above what was attained by pre-capitalist societies. Without the pressure of capital accumulation, the relatively high level of labor productivity may be used to greatly reduce the population's labor time that has to be committed to the production of necessities. This could in turn greatly expand the scope and potential of popular political participation. These historical conditions and possibilities suggest that there could be great hope for the post-capitalist society to be more egalitarian, less exploitative and oppressive, and possibly become one with zero exploitation and oppression.

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Table 1

Selected Energy Indicators

The World's Major Regions and Countries, 2004[a]

Region / Country	Energy Use per Person	Energy Use per Thousand $ of GDP	GDP per Unit of Energy Use
World	1.77	0.21	4,569
OECD	4.73	0.19	5,355
Middle East	2.64	0.37	2,671
Former USSR	3.43	0.49	2,032
Non-OECD Europe	1.92	0.25	3,972
China[b]	1.25	0.23	4,440
Asia	0.63	0.19	5,254
Latin America	1.10	0.16	6,431
Africa	0.67	0.29	3,408
United States	7.91	0.22	4,602
China	1.24	0.23	4,364
Japan	4.18	0.16	6,436
India	0.53	0.18	5,438
Germany	4.22	0.16	6,206
France	4.43	0.16	6,099
United Kingdom	3.91	0.14	7,109
Italy	3.17	0.12	8,109
Brazil	1.11	0.15	6,762
Russia	4.46	0.49	2,041
Myanmar	0.28	0.05	18,883

[a] Energy use is measured by total primary energy supplies in tons of oil equivalent. GDP is measured in 2000 Purchasing Parity Dollars.
[b] Including China and Hong Kong (China).
Source: IEA (2006).

Table 2

World's Metallic Mineral Resources

Metals	Resources[a] (10^6 tons)	Reserve Base[b] (10^6 tons)	Production (10^6 tons)	Years to Depletion[c]		
				Current Rate	Economic Growth	Resources
Antimony	N.A.	3.9	0.117	33	25	N.A.
Arsenic	11	1.65	0.0546	30	23	80
Bauxite	75,000	32,000	165	194	79	116
Beryllium	0.08	0.016	0.000114	141	66	136
Bismuth	N.A.	0.68	0.0052	131	64	N.A.
Cadmium	6	1.8	0.018	100	55	102
Chromium	12,000	797	18	44	31	134
Cobalt	15	13	0.0524	248	90	96
Copper	1,600	940	14.9	63	41	57
Gallium	1	N.A.	0.000063	N.A.	N.A.	290
Germanium	N.A.	N.A.	0.00009	N.A.	N.A.	N.A.
Gold	N.A.	0.09	0.00245	37	27	N.A.
Indium	N.A.	0.006	0.000455	13	11	N.A.
Iron Ore	800,000	370,000	1,520	243	89	123
Lead	1,500	140	3.28	43	31	116
Lithium	14	11	0.0204	539	124	135
Magnesium[d]	12,000	3,600	4.3	837	145	204
Manganese	N.A.	5,200	9.79	531	123	N.A.
Mercury	0.6	0.24	0.001	240	88	129
Molybdenum	18.4	19	0.163	117	60	59
Nickel	130	140	1.5	93	53	50
Platinum Group	0.1	0.08	0.000434	184	77	86
Rare Earths	N.A.	150	0.105	1429	171	N.A.
Rhenium	0.011	0.01	0.000043	233	87	91
Silver	N.A.	0.57	0.0203	28	22	N.A.
Tantalum	N.A.	0.15	0.00191	79	47	N.A.
Tin	N.A.	11	0.28	39	29	N.A.
Titanium[d]	2,000	1,300	5.2	250	90	385
Tungsten	N.A.	6.2	0.0765	81	48	N.A.
Vanadium	63	38	0.0425	894	148	172
Zinc	1,900	460	10.1	46	32	78
Zirconium	60	72	0.87	83	49	43

[a] A concentration of naturally occurring material in or on the earth's crust in such form and amount that economic extraction is currently or potentially feasible.
[b] The part of an identified resource that meets specified minimum physical and chemical criteria related to current mining an production practices, including those resources that are currently economic as well as those that have a reasonable potential for becoming economically available within planning horizons.
[c] Alternative scenarios: depletion of reserve base at current rates of production; depletion of reserve base assuming production growing at 2 percent a year; and depletion of resources assuming production growing at 2 percent a year.
[d] Magnesium compounds and Titanium mineral concentrates respectively.
Source: USGS (2006).

Figure 1
The World's Grain Production
1951-2006