History of Prime Movers and Future Implications

Mikhail V. Shubov
University of MA Lowell
One University Ave,
Lowell, MA 01854
E-mail: mvs5763@yahoo.com

Abstract

Motive and electrical energy has played a crucial role in human civilization. Since Ancient times, motive energy played a primary role in agricultural and industrial production as well as transportation. At that time, motive energy was provided by work of humans and draft animals. Later, work of water and wind power was harnessed. During the 19th century, steam power became the main source of motive energy in USA and Britain. Modern transportation and industry depend on the work of heat engines that use fossil fuel. A brief history of different sources of energy is presented in this work. The energy consumptions in pre-industrial and industrial societies are calculated. The lost opportunities for the Second Industrial Revolution (such as fast breeder reactors and thermonuclear power stations) are discussed. The case that the Solar Power will become the main source of energy by the second half of this century is presented. It is calculated that the Solar Power has the potential to bring about the new Industrial Revolution. Based on material and energy resources available in the Solar System, it is demonstrated that the Solar System Civilization supporting a population of 10 Quadrillion with a high standard of living is possible.

Keywords: motive energy, prime movers, Industrial Revolution, solar power, Solar System Colonization

1 Introduction

Motive energy and mechanical work done by humans, animals, and machines has been one of the defining factors for Human Civilization. At first, humans had to perform work without any assistance. Since Early History of Humankind, work animals were used to carry loads, pull carts, and perform agricultural work. Since 3rd century BCE, water wheel power came into use [1 p.9].

During the XIXth century, there has been a tremendous growth in motive energy production. At that point, steam engines were the main source of power [2 p. 503]. The growth of motive
energy production enabled an unprecedented growth of industry and income per capita. Rapid
growth of motive energy production continued up to about 1970.
Currently, motive energy production is stalled. Modern civilization relies on fossil fuels to
produce motive energy. This energy production can hardly expand. Many scientists believe that
Solar Power will become the main source of energy within a few decades [3, 4, 5]. In this work we
present a case, that Solar Power can not only replace fossil fuels as the main source of energy, but
also enable growth of energy production by a factor of 50 to 150. This energy growth would bring
the Second Industrial Revolution and great increase in gross domestic product (GDP) per capita.
The final stage of Human Civilization would be colonization of Solar System. That would expand
energy production by a factor of about 100 billion. As we discuss in Section 8, Solar System
Civilization would be able to support a population of 10 quadrillion people.

At this point, we present a strict definition of prime movers and motive energy. A prime
mover is any engine producing mechanical power for a vehicle, manufacture, or electricity genera-
tion. Work animals are counted among prime movers, which is relevant for past centuries. In 1850,
about 60% of motive energy in USA was produced by work animals [2, p. 503]. Motive energy is
the total energy produced by prime movers. It also includes all electric energy from any source.

Many sources dealing with modern energy production and consumption confuse motive energy
with heat energy. Thus, electric energy produced by nuclear, hydroelectric, wind, or solar power is
counted at the same rate as potential chemical energy in petroleum or natural gas. This is absolutely
wrong, since most modern engines convert the energy present in fuel into motive or electric energy
at 37% efficiency [6, p.213].

2 Pre-Industrial Age

Working animals have been the most important source of motive energy in pre-Industrial world.
Animals were used for plowing, transportation, and driving mills. Water and wind power were the
other major sources of motive energy.

Water wheels originated in Syria in 3rd century BCE [7]. Water wheel powered hammers
became common in Italy in the 1st century CE [8]. They were common in China at the same time
[9, p.183]. Water powered saw mills became common by 11th century [10]. Fulling mills appeared
in 11th century [11, p.14]. During the Middle Ages, water wheels began powering bellows for blast
furnaces, tool sharpening wheels, drills for making cannons, chopping mills for making paper, and
lathes [12].

In order to estimate the energy production in pre-Industrial World, we must have an estimate for
the time worked by each prime mover. In a developed pre-Industrial society there was about one
water wheel per 300 inhabitants. This number definitely varied by society. Each wheel developed
an average of 3.7 kW and worked 2,200 hours per year [13, p.7961]. Thus water power provided
an average of 27 kWh per year per inhabitant. By far the greatest contribution of wind power was for sailing vessels. An average ship sailed 3,500 hours per year. Average work performed by wind on sailing vessels in developed pre-Industrial societies is approximately equal to 33 kWh per year per inhabitant [13, p.7959]. Once again, there was variance among societies.

Draft animals provided most work in pre-Industrial world. In a developed pre-Industrial society such as USA in mid nineteenth century, there was about 0.25 hp of working animal power per capita [2]. This could be a horse or two bulls per four inhabitants. Obviously, number of animals per capita also varied from place to place. Animals can work up to 6 hours per day. From data in [14, p.11], it follows that an average draft animal in USA 1850 did an equivalent of 900 hours per year full intensity work. In modern India, an average draft animal works 600 hours per year [15, 16]. According to other sources, 660 hours per year is the normal workload for an animal, while 1,200 hours per year can only be sustained by a camel [17]. Based on the data above, draft animals provided an average work of 110 kWh to 160 kWh per year per inhabitant.

A good estimate for the total amount of motive energy per inhabitant in pre-Industrial society is 200 kWh per year, of which 140 kWh came from work animals, 30 kWh from water power and 30 kWh from wind power. In 2017, US motive energy consumption was 20,400 kWh per capita. Of that energy, 12,600 kWh per capita is electricity [18, p.69] and about 7,800 kWh per capita is gas engine work [19, p.144].

The combination of plant photosynthesis and animal metabolism can be considered the Nature’s way of converting solar power to motive energy. This way is very inefficient. Most crops convert only about 0.3% of the energy of sunlight into food calories [20]. Work animals are not efficient engines. From the data presented in [13, p.7958] and [14, p.11], it follows that only 6.5% of energy in draft animal feed was converted to useful work. Other sources studying modern India estimate draft animal efficiency at 4.0% [21] to 5.0% [22]. Overall, 0.02% of solar energy is converted into motive work. A modern 16% efficient photovoltaic cell has 800 times greater efficiency.

Some modern researchers suggested growing energy rich crops and using them to produce diesel fuel. The best choice among current crops is palm oil. The system would be 0.45% efficient [23, p.23]. A system using algae can be 1.5% efficient [24, 25, p.6]. This still requires very much work, and is still vastly inferior to photovoltaic cells. Algae is best suited for producing feed for pigs, poultry, cattle and fish [24, p.23], but it can not compete with photovoltaic cells in harvesting solar power.

3 Steam Power

In 1698, Thomas Savery invented a steam pump. Savery pumps did not work autonomously – they required an attendant switching two valves at regular intervals. Savery pumps had a power
of 0.7-0.8 kW. These pumps were mostly used to pump water out of mines [26, p.4]. The first practical steam engine was invented by Thomas Newcomen in 1712 [27]. First Newcomen engines had a power of 4 kW, while some later ones produced up to 56 kW [26, p.7].

Steam engine was further improved by James Watt in 1760s and 1770s [28]. By 1800, 496 Watt engines have been produced. These engines had 5-10 kW power [26, p.9]. In 1797, Robert Trevithick invented the first high pressure steam engine [26, p.6]. In a high pressure stem engine, steam expands in a cylinder and thus performs work. All previous engines were atmospheric steam engines. In an atmospheric steam engine, steam condenses and creates partial vacuum within a cylinder. The atmosphere does work on a piston by pushing it inside [27]. In 1849, the steam engine was further improved by George Corliss [29]. In 1862, Porter and Allen developed a high speed steam engine [30].

Efficiency of steam engines improved over time. Savery pumps had efficiency below 0.5% [26, p.4]. Original Newcomen engines had efficiency of 0.5%. Later Newcomen engines improved by Smeaton had efficiency of 1% [26, p.7]. Watt engines had efficiency of 2% to 3% [31, p.87]. By 1840s, top steam engines had efficiency of 12% [26, p.15]. When steam engines were used to drive factory machinery, most energy was lost in transitions. The efficiency of factories, which included both the engine and the mechanical transitions was much lower. In in USA 1900, factory efficiencies averaged 4% [2, p. 354].

The number of steam engines and their cumulative power grew rapidly. By 1800, there were about 600 steam engines in the World, mostly in Britain. By 1810, the number of steam engines grew to about 5,000 [26, p.16]. By 1810s, steam was still not a significant source of motive energy – like solar power is still not a significant source of electricity in 2020. By 1840, 570 MW steam power was installed in USA and 650 MW in Europe. By 1870, 4,200 MW steam power was installed in USA and 8,800 MW in Europe. By 1896, 13,500 MW steam power was installed in USA and 30,200 MW in Europe [26, p.16]. Hopefully, solar power will be the primary source of energy at the end of this century. For now, figures for the years 2040, 2070, and 2096 are not available.

Steam power played a key role in Great Britain’s Industrial Revolution. By 1850, steam power was used in a wide variety of manufacturing. It was used in food industry, tobacco manufacture, textile industry, lumber and wood products, paper production, chemical industry, and metal working [36, p. 458].

Steam turbines had been introduced in 1884 by Sir Charles Parsons [32]. First steam turbines were very inefficient and had low power. By 1900, a 1.3 MW turbine was built. By 1907, a 13 MW turbine was built. The first gigawatt turbine was built in 1965. Steam turbine efficiency grew from 12% in 1900 to 30% in 1930 to 42% in 1973 [26, p. 38-39]. Most electrical energy in 2019 is generated by power plants using steam turbines.

Steam turbines are likely to have an important role to play during Space Age and colonization.
of the Solar System. In outer space, energy can be generated by turbines using potassium vapor as the working fluid. The cycle is closed. Potassium is heated either by nuclear or concentrated solar energy \[33, 34, 35\].

### 4 Fossil Fuel Era

During the First Industrial Revolution, rapid growth of energy production was enabled by the use of the heat engines powered by fossil fuel. These heat engines could produce much more power than waterwheels, windmills, and work animals.

Between 1849 and 1923, the total power of engines installed in industry grew 68 times \[37\] p. 30. Between 1849 and 1955, the total power of prime movers used in American Industry and transportation grew by a factor of 840. This factor overestimates the actual growth of motive energy production. In 1955, 93% of all power of prime movers was in automobile engines \[2\] p. 503. On average automobiles work only a small fraction of time, and do not use their full power.

According to detailed studies, 6.7 billion kWh of motive energy has been produced in USA 1850 \[14\] p.11. The total motive energy produced in 1956 can be calculated from mineral fuel production. The heating value of mineral fuel produced in USA 1955 is 11.0 trillion kWh \[2\] p. 354. About 42% of this value has been converted to motive energy \[14\] p.70 at an average efficiency of 28% \[2\] p. 507. Overall, 1.3 trillion kWh of motive power has been produced in USA, 1955. Between 1850 and 1956, the total energy motive energy produced in USA increased by a factor of 195. Between 1890 and 1980, GNP and energy consumption in USA have been closely correlated \[38\] p.6. Among modern Nations, energy consumption per capita is almost proportional to GDP per capita to the power 0.78 \[1\] p.20].

In USA 1900 to 1955, total mineral fuel production grew by a factor of 5.0. During the same time, the average efficiency of electric power production grew from 4% to 28% \[2\] p. 354. By 2011, the average efficiency has grown to 35% \[39\] p.326 – which indicates very slow progress. The efficiency of an electric power production is the product of the prime mover efficiency, the electric generator efficiency, and grid transmission efficiency. Generator efficiencies are generally above 90%. By 1911, alternating-current generators had efficiencies of 94% to 96% \[40\] p.43. Efficiency of electric power use in industry has also undergone significant improvement over the last century \[41\].

Between 1973 and 2017, global fossil fuel consumption grew from 71 trillion kWh to 162 trillion kWh in thermal energy equivalent \[18\] p.8. During the same time, electric power generation efficiency grew from 32.7% to 37.0% \[6\] p.213. Combining the aforementioned data, we conclude that motive energy equivalent grew from 23 trillion kWh to 60 trillion kWh between 1973 and 2017. Electric power generation itself grew from 6.1 trillion kWh to 25.6 trillion kWh during these years \[18\] p.30.
Sustaining economic growth based on fossil fuels is impossible. Increasing the consumption of fossil fuels will lead to their depletion. Increasing the efficiency of prime movers is a slow and expensive process.

5 Motive Energy in Transportation

Work animals have been used for pulling carts for about four millennia [43]. Wind power has been used to propel sailing vessels since Ancient Egyptian times [44].

The real proliferation of steam transportation came only with the introduction of railroads and steam locomotives. Richard Trevithick, who invented the high pressure steam engine built the first railroad locomotive in 1804. It pulled five wagons weighing 10 tons for a distance of 16 km at a speed of 8 km/h [26, p.10].

First railroads in Britain and USA were built in late 1820s. By 1840, USA contained 2,800 miles of railroads, by 1850 – 9,000 miles, by 1860 – 30,000 miles and by 1900 almost 200,000 miles. Railroad development was sped up by a fast growth in steel production during the second half of XIXth Century [42, p. 133]. Speeds which have been unimaginable earlier became reality. By mid 19th century, train speeds of up to 100 km/h became common [26, p.19].

Number of passenger-miles rose more rapidly than the length of railroads. It rose from 470 million passenger-miles in 1849 to 1.9 billion passenger-miles in 1859 and 12 billion passenger-miles in 1890 [45, p. 585]. The first diesel locomotive appeared in 1925. By 1957, diesel locomotives were 10 times as numerous as steam locomotives [2, p.429]. Even though passenger cars have displaced trains as the primary mode of passenger transportation since 1920s, trains remain important in freight transport. The amount of freight moved by train tripled between 1960 and 2006 [19, p.9].

In USA, first steam ship went afloat in 1809. By 1840, 10% of all American ships were steam-powered. In 1893, for the first time, steam ships outnumbered sailing ships [2, p.445].

Electric Streetcar Revolution started in 1888 and spread rapidly [46]. By 1902, there were almost 60,000 electric street cars in USA, which carried 4.5 Billion passengers that year [47, p.6]. The street cars travelled 1.1 Billion miles [47, p.12].

Automobiles were first proposed by Leonardo da Vinci [48, p.7]. In 1769, Nicolas-Joseph Cugnot built the first steam-powered car [48, p.8]. During 1830s, Walter Hancock built three steam-powered passenger buses which were much more successful and less expensive than contemporary horse-drawn buses [49]. The buses travelled at an average speed of 10 mph. They travelled an average of 53 miles per day. Each bus carried an average of 30,000 passengers and performed 180,000 passenger-miles per year [50, p. 77]. Walter Hancock planned to expand his omnibus line to about 80 steam carriages [50, p. 86]. In 1831, H.T. Alken predicted that steam automobiles would soon displace horse transportation [51].

Both Walter Hancock’s plan and H.T. Alken’s prediction failed. For many decades, the auto-
motive age did not come. Some technological projects are impossible at the time of their conception. Nevertheless, almost all of these projects become possible as technology advances. Automotive age did come. In 1960s and 1970s, many futurists believed that Space Age is coming soon [52, 53, 54]. It still has not come. Success in once abandoned projects should give us hope.

The first gasoline-powered car was first built in 1885 [48, p.8]. At first car production was slow. Henry Ford build an assembly line which produced Model T cars in large numbers [61]. In USA, the number of automobiles rose from 8,000 in 1900 to 458,000 in 1910, 8.1 million in 1920, 23 million in 1930, and 56 million in 1957 [2, p.462]. In 2012, there were 254 million motor vehicles in USA [19, p.9].

The next great challenge in transportation technology is the ability to transport astronauts and payload into outer space at reasonable cost. The first successful space launch took place on October 4, 1957 – a Soviet satellite named Sputnik was placed in orbit [55]. In 1961, the first astronaut named Yuri Gagarin went to space [56]. American Lunar Expedition took place in 1968.

Unfortunately, launch costs, which are the costs of placing payload into Earth’s orbit remained high. Up to 2010s launch costs remained at an average of $18,500 per kg up to about 2010 [57, p.8]. A breakthrough in launch cost reduction was accomplished by SpaceX company. By 2009, their Falcon 9 rocket delivered payload to LEO for $2,700 per kg. The next step was the introduction of the reusable first stage. On December 21, 2015, SpaceX made a huge step in History when the first stage of Falcon 9 spacecraft returned to the launching pad [58, p.1]. During 2016, SpaceX has successfully landed six first stage boosters [59]. By July 2019, there have been 34 successful first stage returns out of 40 attempts [60]. By 2018, SpaceX was offering LEO delivery at $1,400 per kg via Falcon Heavy [57, p.8].

Many engineers promised drastic reduction of launch costs for decades. At this point we can not predict the future development of technology and launch cost reduction. It is possible that True Space Age and colonization of Solar System will occur during the next Energy Revolution.

6 Nuclear Power – a Lost Chance

The first nuclear power plant in USA was built by 1957. By 1970, 20 nuclear power plants operated. By 1980 there were 71 nuclear power plants, and 112 nuclear power plants by 1990 [39, p.271]. Electricity generation by the nuclear power plants increased even more rapidly. In 1957, the nuclear power plant generated 0.2 billion kWh. In 1970, nuclear power plants generated 22 billion kWh. These plants generated 250 billion kWh in 1980 and 577 billion kWh in 1990 [39, p.273]. Continued growth of nuclear power production could have started the new Industrial Revolution. Nuclear Power Revolution could have started in 1990s and continued during the first decades of this Century. Unfortunately, the Nuclear Power Revolution came to an abrupt end before it really started. Nuclear share of total net generation has not changed much since 1988 [39, p.273].
In order to understand the fizzling of Nuclear Power, we must have basic understanding of nuclear reactors. There are several types of nuclear reactors. The author’s paper [62] was on the subject of Accelerator Breeder Reactors. Other reactor types relevant to this article are Thermal Reactors and Fast Breeder Reactors discussed in paragraphs below.

In all nuclear reactors, a chain reaction of nuclear fission is sustained. When a fissile nucleus absorbs a neutron, it is likely to undergo a nuclear fission event. Examples of fissile nuclei are $^{233}$U, $^{235}$U, and $^{239}$Pu. A nuclear fission produces several secondary neutrons. The average number of secondary neutrons produced depends on the energy of absorbed neutron and the nucleus undergoing fission. Generally, the average number of secondary neutrons per fission is 2.4 to 2.9. Some of the secondary neutrons are lost, while others cause further fission reactions. In a sustained nuclear fission, the number of neutrons absorbed is about the same as the number of neutrons produced. The total neutron flux changes very little over time.

In Thermal Nuclear Reactors, the neutrons are slowed down before they cause a nuclear fission. Neutrons can be slowed down by multiple collisions with nuclei. Thermal reactors are by far the most common ones. In Fast Breeder Reactors, the chain reaction is sustained by fast neutrons. In Accelerator Breeder Reactors, the nuclear chain reaction is not self-sustaining. This reaction is sustained by an external source of neutrons. That source of neutrons consists of a uranium target subject to a stream of super energetic protons. These protons have energy of about 1 GeV. This proton stream is produced by an accelerator. Whenever a super energetic proton strikes a heavy nucleus it causes the nucleus to disintegrate into many light fragments and neutrons [62, p.8-13].

All reactors consume fissile nuclei such as $^{235}$U, $^{233}$U, and $^{239}$Pu. Most reactors also produce fissile nuclei from fertile nuclei. Examples of fertile nuclei are $^{232}$Th and $^{238}$U. When $^{232}$Th absorbs a neutron, it becomes $^{233}$Th, which decays to $^{233}$U – a fissile nucleus. When $^{238}$U absorbs a neutron, it becomes $^{239}$U, which decays to $^{239}$Pu – a fissile nucleus.

In Thermal Nuclear Reactors, consumption of fissile nuclei greatly exceeds production of fissile nuclei from fertile nuclei. In Fast Breeder Reactors, and more so in Accelerator Breeder Reactors, production of fissile nuclei from fertile nuclei considerably exceeds consumption of fissile nuclei. As a result, Thermal Nuclear Reactors must use the resources of fissile nuclei. Fast Breeder Reactors and more so in Accelerator Breeder Reactors can use the resources of fertile nuclei. Fertile nuclei are much more common in nature than fissile nuclei. The only naturally occurring fissile isotope is $^{235}$U, which makes up 0.7% of all uranium found in nature. The rest of natural uranium is fertile $^{238}$U [62, p.6]. In terms of global energy reserves, $^{235}$U contains 21 times less energy than coal [63, p.17]. Reserves of fertile isotopes are virtually unlimited. A ton of average rock contains 18 g of thorium, and 3 g of uranium. That is an energy equivalent to 45 tons of coal [62, p.8]!

Thermal Nuclear Reactors may be useful for limited applications. They are useful for marine propulsion [64]. Nevertheless, they can not replace fossil fuel as the main source of energy due to lack of sufficient resources of $^{235}$U. In the author’s work on nuclear reactors [65], a case was made
that thermal nuclear reactors could be very useful for space propulsion.

The author also made a case against proliferation of thermal nuclear reactors on Earth – $^{235}$U consumed in these reactors will deplete a fuel resource needed for space transportation [65, p. 102]. Total resources of uranium producible at $130 per kg or less is 6,140,000 tons [67, p. 15]. In 2019, Thermal Nuclear Reactors consumed $^{235}$U contained in 67,000 tons of uranium [66]. By the time $^{235}$U will be needed for space exploration, most uranium resources may be depleted.

No Accelerator Breeder Reactors have been built. In December 2019, there are 444 nuclear reactors in the World with total power of 395 GW [66]. There are also 6 Fast Breeder Reactors in the World with total power of 2 GW [68]. Fast Breeder Reactors held a promise of providing unlimited energy supply [69].

Nuclear Fusion power also seemed very promising. According to a 1960 report, there should be about 250 nuclear fusion power plants in Europe in 20 years [70]. Some people are still optimistic about this source of energy, while others have given up hope. One of the main reasons why Nuclear Fusion did not succeed is that it has received very little funding. Between the years 1975 and 1982, the average annual budget for fusion power in USA was $1 billion per year, after which the funding fell rapidly [71]. Between the years 2000 and 2012, the average annual budget for fusion power in USA was $300 million to $400 million per year [72]. According to a 1976 plan for development of nuclear fusion power, these levels of funding would never achieve result [73, p. 12]. In Europe, a giant thermonuclear power station called ITER is being constructed. It’s total cost of $22 Billion is covered by 35 Nations. It is supposed to start working in 2035 [74].

In the author’s opinion, Nuclear Fusion based Energy Revolution would have succeeded if it had more funding. Many experts agree [75, 76, 77, 78]. Had funding for Fusion Power been at least $30 Billion per year since 1980, it is likely that Fusion Power Revolution would have started by the turn of the century.

7 Future Prospect – Solar Power Revolution

Energy production has little chance for growth in the coming decades. Almost all of the energy comes from fossil fuels, which are in a very limited supply. Total reserves of fossil fuel can sustain 82 years of use at current rate [18, 63]. The world may contain up to 17 trillion tons of hard coal [63, p. 28], but using this reserve is likely to cause enormous global warming.

The technology which has a potential for totally transforming energy production is harvesting of Solar Power. In order to understand the possible impact of Solar Power Revolution, we must compare the amount of motive power produced in Modern World to the amount of motive power which can be produced by Solar Power. As we have mentioned earlier, global energy consumption is equivalent to 60 trillion kWh of motive energy per year. If all of Earth’s deserts are covered with 16% efficient photovoltaic cells, then the total electricity production would be 5.0 quadrillion kWh.
per year.

A very interesting technology is Floating Solar Power – solar power stations floating on water. Currently, only 0.4% of all Photovoltaic power is produced by floating solar power stations [79]. By the end of Solar Power Revolution, Floating Solar Power may become the main energy source. If 20% of World Ocean is covered by 16% efficient photovoltaic cells, then the total electricity production would be 10.0 quadrillion kWh per year. This is twice as much as we can obtain from deserts. All deserts and 20% of ocean can bring 15 quadrillion kWh per year, which is 250 times greater than modern motive power production.

In 2017, worldwide, Solar Power produced about 2.5% of global electricity and 0.9% of global motive energy. That year 531 billion kWh of electricity was produced by solar power [80, p.76-77]. Solar Power production has been growing by an average of 44% per year since 1992. It has been growing by an average of 32% between 2012 and 2017 [80, p.82].

At the time, the cost of installed photovoltaic power fell rapidly. Between 2010 and 2018, the cost of installed solar power for utility-scale stations fell from $4.63 per Watt to $1.06 per Watt [81, p.viii]. During the same time, the prices of solar modules themselves dropped from $2.47 per Watt to $0.47 per Watt. The main breakthroughts came between 2010 and 2013 and in 2016 [81, p.43]. By December 2019, most module prices fell to $0.28 per Watt. Electric energy produced by Solar Power Stations has an average production cost of 5 cents per kWh. Cost decrease has surpassed the 2020 target [81, p.39]. Between 2010 and 2018 the average efficiency of the new photovoltaic modules installed in utilities in California grew from 13.8% to 19.1% [81, p.5].

If the growth rate of 20% per year can be sustained for 20 years, then Solar Power would produce most of electric energy by 2040. That year about 40 trillion kWh electric energy should be produced by Solar Power. If the energy production by other prime movers will remain relatively unchanged, the global motive energy production in 2040 should be about 100 trillion kWh. The most likely scenario is that after that Solar Power production will continue to grow. This will mean the growth of overall power production. This will likely drive the Second Industrial Revolution. The growth of Solar Power will continue until it will reach the natural limit of 15.0 quadrillion kWh described above.

How long will Second Industrial Revolution take? Obviously, we have no way of knowing. Most past predictions about the present did not come true. Nevertheless, we can make a judgement based on historical precedent. As we have mentioned earlier, between 1850 and 1956, the total energy production by prime movers in USA grew by a factor of 210 [2, p.507]. This corresponds to a growth rate of 66% per decade. If global production of motive energy grows at the same rate during the Second Industrial Revolution, then it will take from 2040 to 2140 for motive energy production to grow from 100 trillion kWh to 15.0 quadrillion kWh. Obviously, we can neither rule out faster nor slower growth. Hopefully, the Solar Power Revolution will not fizzle like Fast Breeder Reactors and Fusion Power. Only time will tell.
8 The Final Frontier

Colonization of the Solar System is the Final Frontier for Humankind. Resources contained within the Solar System are vastly greater then resources available within Earth’s crust. The total solar energy available in space exceeds the solar energy available on Earth by a factor of a billion.

The Solar System will provide a new home for most humans, even though Earth will remain an important cultural center. Humans will live on billions of large habitats orbiting the Sun. Each of these habitats will harvest solar energy. Each habitat will produce all necessary food, drinking water, and oxygen needed for humans and animals. Some goods will be produced on specialized factory habitats and distributed to other habitats. This concept is called the Dyson Sphere [83]. The concept of Solar System Civilization was first envisioned by Konstantin Tsiolkovsky in 1903 [84]. During 1970s, many elaborate models of Solar System Civilization were published [85, 86].

For the rest of this Section, we use the term Exaton, which is $10^{18}$ tons. The Asteroid Belt contains about $3 \text{ Exatons}$ of material composed of metal silicates, carbon compounds, water, and pure metals [87]. Most of asteroids are of a carbonaceous type [88]. Carbon is very useful for production of food for space travelers, fuel for propulsion within space, and plastics for space habitat structures. High quality steel is also an abundant resource in space. For example, asteroid 16 Psyche contains $10^{16}$ tons of nickel-rich steel [89]. Initially, asteroidal material would be sufficient for construction of space-based habitats. Additional material for comfortable habitats can be obtained from Mercury, satellites of gas giant planets, and Kuiper Belt objects [90]. Kuiper Belt contains about $120 \text{ Exatons}$ of material – mainly water, ammonia, and carbon compounds [91]. Planet Mercury contains 330 Exatons of material composed of metal silicates, carbon compounds, and pure metals [93, p.14-2]. Satellites of Jupiter and Saturn contain at least 10 Exatons of water and hydrocarbons [93, p.14-4]. Given the data above, it is possible to construct a total habitat space of 100 Exatons. It has been estimated that Solar System resources can easily sustain a population a million times greater than the global population of today [94]. Each inhabitant will have space provided by 10,000 tons of structure. The mass of modern luxury cruise liners can be approximated by multiplying 85 tons by the number of cabins [92]. Space habitats will have about 120 times more structural material per inhabitant, and habitat material will be more advanced. This will provide material standard of living suitable for Solar System Civilization.

As we have discussed in this article, the most important resource for industry and civilization is energy [95, 96]. Sunb’s thermal power is $3.86 \cdot 10^{26} \text{ W}$ [93, p.14-2]. A future civilization, which would harvest 1% of that power with 15% efficiency, will have energy production of $5 \cdot 10^{24} \text{ kWh/year}$. With Solar System Civilization being a home to about $10^{16}$ inhabitants, the motive energy consumption per capita would be 500 million kWh per year. As we have mentioned in Section 2, energy consumption in USA 2019 is 20,400 kWh per year per capita – almost 25,000 times less. Nevertheless, life in a space habitat would require much more energy. People at that
time will likely view our material standards of living as rudimentary and poor.

When will Solar System Colonization take place? In the author’s opinion, technology to start colonization of Solar System existed since 1970s. Many contemporary experts agreed [85, 86]. Elon Musk believes that colonisation of Solar System can start in 2020s [97, 98, 99]. Each new invention and technology makes initial steps of Solar System Colonization more feasible. The new Energy Revolution should create both capital and improve technology for Solar System Colonization.

We do not know when the Solar System will be colonised, but we can look for historical precedent. Maritime technology of Ancient World may have been sufficient to sail to America [100]. Leif Erikson discovered America in the beginning of the 10th century [101]. Possibly, the Vikings could have started colonization of North America in 11th century. Colonization of South America began after Columbus’ discovery of the continent [102]. If colonization of America did not start at that time, it definitely would have started in the 17th or 18th centuries. As for colonization of the Solar System, only time will tell.

References

[1] Agnoletti, M., Neri Serneri, S., Eds., The Basic Environmental History, Springer, Heidelberg, New York, London, 2014.

[2] Historical Statistics of the United States: Colonial Times to 1957; a Statistical Abstract Supplement, Bureau of the Census with the Cooperation of the Social Science Research Council, Washington, 1960.

[3] Barnham, K., The Burning Answer: The Solar Revolution: a Quest for Sustainable Power, Pegasus Book LLC, New Yourk, 2015.

[4] Bradford, T., Solar Revolution: The Economic Transformation of the Global Energy Industry, Cambridge, Mass: the MIT Press, 2008.

[5] McKevitt, S., The Solar Revolution: One World. One Solution. Providing the Energy and Food for 10 Billion People, Thriplow: Icon Books, 2014.

[6] Monthly Energy Review, December 2019, Washington, D.C: United States, Energy Information Administration, 2020.

[7] de Miranda, A., Water architecture in the lands of Syria: the water-wheels, L’Erma di Bretschneider, p. 37–8, 2007.

[8] Wilson, A., Machines, Power and the Ancient Economy, The Journal of Roman Studies, 92(16), p. 1-32, 2002.
[9] Needham, J., Wang, L., *Science and Civilisation in China: Volume 4, Part 2*, Cambridge: Cambridge university press, 1965.

[10] Lucas, A.R., Industrial Milling in the Ancient and Medieval Worlds: A Survey of the Evidence for an Industrial Revolution in Medieval Europe, *Technology and Culture, 46*(1), p. 1-30, 2005.

[11] Gimpel, J., *The Medieval Machine: The Industrial Revolution of the Middle Ages*, New York: Penguin Books, 1977.

[12] Reynolds, T. S., *Stronger Than a Hundred Men: A History of the Vertical Water Wheel*, Johns Hopkins University Press, London, 2003.

[13] O’Connor P.A., Cleveland C.J., U.S. Energy Transitions 1780–2010, *Energies, 7*(12), p. 7955-7993, 2014.

[14] Ayres, R.U., Ayres, L.W., Warr, B., Exergy, power and work in the US economy, 1900–1998, *Energy, 28*(3), p. 219–73, 2003.

[15] Panchasara, H.H., Phaniraja, K.L., Indian Draught Animals Power, *Veterinary World, 2*(10), p. 404-407, 2009.

[16] Ramaswamy, N.S., Draught animals and welfare, *Revue Scientifique et Technique de l’Office International, 13*(1), p. 195-216, 1994.

[17] Netam, A., Jaiswal, P., Role of animal power in the field of agriculture, *International Journal of Avian & Wildlife Biology, 3*(1), p. 62-63, 2018.

[18] *Key World Energy Statistics 2019*, International Energy Agency, 2019. 
<https://www.connaissancedesenergies.org/sites/default/files/pdf-actualites/Key_World_Energy_Statistics_2019.pdf>
Accessed Jan 20, 2020.

[19] Moore, W., Ed., *Transportation Statistics Annual Report*, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC, 2013. 
<https://www.bts.dot.gov/sites/bts.dot.gov/files/legacy/TSAR_2013.pdf>
Accessed Jan 20, 2020.

[20] *World Agricultural Production*, United States Department of Agriculture, 2020. 
<https://apps.fas.usda.gov/psdonline/circulars/production.pdf>
Accessed Jan 20, 2020.
[21] Guruswamy, L. D., Neville, E., Eds., *International Energy and Poverty: The Emerging Contours*, Routledge Press, 2017.

[22] Ramakrishna, G. V., *Two Score and Ten: My Experiences in Government*, New Delhi: Academic Foundation, 2004.

[23] Oilgae Comprehensive Report, *Energy from Algae: Products, Market, Processes and Strategies*, Oilgae, Tamilnadu, India, 2011.

[24] Landesman, L., *Alternative Uses for Algae Produced For Photosynthetic CO₂ Mitigation*, 2008.
Formerly available at <http://wwwri.nrcce.wvu.edu/conferences/2008/WRRI/pdf/presentations/Landesman.pdf>

[25] D’Elia, L.N., Keyser, A.D., Young, C.P., *Algae Biodiesel*, 2010.
<https://digitalcommons.wpi.edu/iqp-all/3330>
Accessed Dec 26, 2019.

[26] Lovland, J., *A History of Steam Power*, 2007
<http://folk.ntnu.no/haugwarb/TKP4175/History/history_of_steam_power.pdf>
Accessed Dec 25, 2019.

[27] Rolt, L.T.C., Allen, J.S., *The Steam Engine of Thomas Newcomen*, Ashbourne: Landmark, 1997.

[28] Rolt, L.T.C., Watt, J., *James Watt*, New York: Arco Pub. Co, 1964.

[29] Rosenberg, N., Trajtenberg, M., *A General Purpose Technology at Work: The Corliss Steam Engine in the Late 19th Century US*, Cambridge, Mass: NBER, 2001.

[30] *The High Speed System of Steam Engineering: Directions for Setting and Running the Porter-Allen Steam Engine*, Philadelphia: Press of Times Printing House, 1920.

[31] Dickinson, H. W., *A Short History of the Steam Engine*, Cambridge University Press, Cambridge, UK, 2019.

[32] Osler, A. G., Grieve, G.R., *Sir Charles Parsons’ Workbook*, London: City of London Polytechnic, 1978.

[33] Moor, B. L., Schnetzer, E., *Three-stage Potassium Vapor Turbine Test*, Defense Technical Information Center, Ft. Belvoir, 1971.
[34] Fraas, A.P., Burton D.W., LaVerne M.E., Wilson, L.V., *Design Comparison of Cesium and Potassium Vapor Turbine-Generator Units for Space Power Plants*, Oak Ridge National Laboratory, 1969.

[35] Supak, K.R., *Reduced Gravity Rankine Cycle System Design and Optimization Study with Passive Vortex Phase Separation*, College Station, Texas: Texas A & M University, 2008. <https://pdfs.semanticscholar.org/1124/0c59b699caed7ef7b8df143c255fbbaa5d310.pdf> Accessed Jan 20, 2020.

[36] Brady, D. S., *Output, Employment, and Productivity in the United States after 1800*, New York: National Bureau of Economic Research, 1966.

[37] Daugherty, C.R., Davenport, R.W., Horton, A.H., *Power Capacity and Production in the United States: Papers*, Washington: U.S. Government Printing Office, 1928.

[38] Devine, W.D., *An Historical Perspective on the Value of Electricity in American Manufacturing*, Oak Ridge, Tenn: Institute for Energy Analysis, Oak Ridge Associated Universities, 1982.

[39] *Annual Energy Review 2011*, United States, Energy Information Administration, Washington, D.C, 2012. <https://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf> Accessed Jan 20, 2020.

[40] *Steam Turbines*, The Industrial Press, New York City, 1911.

[41] Ayres, L.W., Ayres, R.U., Pokrovsky, V., *On the Efficiency of Us Electricity Usage Since 1900*, IR-04-027, 2004.

[42] Croscup, G. E., and Lewis, E. D., *History Made Visible: United States History with Synchronous Charts, Maps and Statistical Diagrams*, Windsor Publing Co, New York, 1911.

[43] Hofmann, D., Fowler, C., Harding, J., Eds., *The Oxford Handbook of Neolithic Europe*, Oxford University Press, Oxford, UK, 2015.

[44] Ahmed, M. Y. Z., Parker, B., *Tourism and Travel in Ancient Egypt: Travel Like an Egyptian*, LAP Lambert Academic Publishing, 2017.

[45] Brady, D.S., Ed., *Output, Employment, and Productivity in the United States After 1800*, National Bureau of Economic Research, New York, 1966.

[46] Middleton, W.D., *Frank Julian Sprague: Electrical Inventor and Engineer*, Indiana University Press, Bloomington, 2009.
[47] Martin, T. C., Durand, E.D., *Street and Electric Railways 1902*, Government Printing Office, Washington, D.C., 1905.

[48] Fallon, M., *Self-driving Cars: The New Way Forward*, Twenty First Century Books, Minneapolis, MN, 2019.

[49] Evans, F. T., Steam road carriages of the 1830s: Why did they fail? *Transactions of the Newcomen Society*, 70, p. 1-25, 1998.

[50] Hancock, W., *Narrative of Twelve Years’ Experiments, (1824-1836): Demonstrative of the Practicability and Advantage of Employing Steam-Carriages on Common Roads: with Engravings and Descriptions of the Different Steam-Carriages Constructed by the Author, His Patent Boiler, Wedge-Wheels, and Other Inventions*, J. Weale, London, 1838.

[51] Alken, H.T., *A View in Regent’s Park*, London, 1831.

[52] Brand, S., *Space Colonies*, Whole Earth Catalog, Sausalito, California, 1977.

[53] Heppenheimer, T. A., *Colonies in Space*, Warner Books, New York, 1978.

[54] Halacy, D.S., *Colonization of the Moon*, Van Nostrand, Princeton, 1969.

[55] Dickson, P., *Sputnik: The Shock of the Century*, University of Nebraska Press, Nebraska, 2019.

[56] Feldman, H., *Yuri Gagarin: The First Man in Space*, Power Kids Press, New York, 2003.

[57] Jones, H.W., "The Recent Large Reduction in Space Launch Cost," *48th International Conference on Environmental Systems*, 8-12 July 2018.

[58] Woodward, D., *Space Launch Vehicle Design*, Dissertation at Department of Mechanical and Aerospace Engineering University of Texas at Arlington, 2017.

[59] Wall, M., A Sixth Success! SpaceX Again Lands Rocket on a Ship at Sea, *space.com*, August 14, 2016.

[60] Falcon, *Wikipedia: The Free Encyclopedia*. Wikimedia Foundation, <https://en.wikipedia.org/wiki/Falcon_9>, Accessed 23 July 2019.

[61] Brooke, A. L., *Ford Model T: The Car That Put the World on Wheels*, St. Paul: Motorbooks, 2008.
[62] Shubov, M., *Accelerator Driven Nuclear Energy Systems*, Texas Tech University, Masters Thesis, 2000.

[63] Andruleit, H., *Reserves, Resources and Availability of Energy Resources: Energy Study 2013*, DERA, Hannover, 2013.

[64] Alam, S. B., Parks, G., *The Design of Reactor Cores for Civil Nuclear Marine Propulsion*, University of Cambridge, Cambridge, UK, 2018.

[65] Shubov, M., *Gas Core Reactors for Deep Space Propulsion*, *International Journal of Advanced Technology & Science Research*, 1(1), p. 63-108, 2019. 
<https://ijatsr.org/assets/papers/jan-2019/ijatsr_01__06.pdf>  
Accessed Dec 23, 2019.

[66] *World Nuclear Power Reactors & Uranium Requirements, December 2019*, World Nuclear Association, 2019.  
<https://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx>  
Accessed 30 December 2019.

[67] *Uranium 2018: Resources, Production and Demand*, Nuclear Energy Agency and International Atomic Energy Agency, 2019.  
<https://www.oecd-nea.org/ndd/pubs/2018/7413-uranium-2018.pdf>  
Accessed 20 Jan 2020.

[68] *Fast Neutron Reactors*, World Nuclear Association, 2019.  
<https://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx>  
Accessed 30 December 2019.

[69] Till, C. E., Chang, Y.I., *Plentiful Energy: The Story of the Integral Fast Reactor: the Complex History of a Simple Reactor Technology, with Emphasis on Its Scientific Basis for Non-Specialists*, CreateSpace, Charleston, SC, 2012.

[70] *Summary of the Euratom General Report for 1960*, Washington, D.C: European Community Information Service, 1960.

[71] Grandoni, D., Why It’s Taking The U.S. So Long To Make Fusion Energy Work, *Huffington Post*, 2017.  
<https://www.huffpost.com/entry/fusion-energy-reactor_n_6438772>  
Accessed Dec 23, 2019.
[72] Holland, A., A Tough Budget for Fusion, *American Security Project*, 2012.  
<https://www.americansecurityproject.org/the-budget-for-fusion/>  
Accessed Dec 23, 2019.

[73] Dean, S.O., Fusion Power by Magnetic Confinement: Program Plan, *Journal of Fusion Energy*, 17(4), 1998.

[74] Claessens, M., *Iter: the Giant Fusion Reactor: Bringing a Sun to Earth*, Springer Nature, Switzerland, 2020.

[75] van Lierop, W., *Fusion Energy: Who Has The Courage To Take It To Market?* Forbes,  
Aug 21, 2019.  
<https://www.forbes.com/sites/walvanlierop/2019/08/21/fusion-energy-who-has-the-courage-to-take-it-to-market/>  
Accessed Dec 23, 2019.

[76] Beck, M., Finding the funding for fusion energy, *E&E News*, March 29, 2016  
<https://www.eenews.net/stories/1060034711>  
Accessed Dec 23, 2019.

[77] Tomlinson, C., Fusion fizzling for lack of funding, *Houston Chronicle*, March 14, 2017.  
<https://www.chron.com/business/columnists/tomlinson/article/Potential-of-fusion-energy-slipping-away-10998236.php>  
Accessed Dec 23, 2019.

[78] Olynyk, G., Fusion research is a wise investment, *The Tech*, Mar. 6, 2012.  
<https://thetech.com/2012/03/06/olynyk-v132-n9>  
Accessed Dec 23, 2019.

[79] *Where Sun Meets Water: Floating Solar Market Report*, Washington, D.C: The World Bank, 2019.

[80] *Trends 2018 in Photovoltaic Applications, Survey Report of Selected IEA Countries between 1992 and 2017*, Report IEA PVPS T1-34:2018, Photovoltaic Power Systems Programme, 2018.

[81] Fu, R., Feldman, D., Margolis, R.M., *US Solar Photovoltaic System Cost Benchmark: Q1 2018*, NREL/TP-6A20-72399, National Renewable Energy Laboratory, Golden, CO, 2018.  
<https://www.nrel.gov/docs/fy19osti/72399.pdf>  
Accessed Jan 20, 2020.
[82] Module Price Index, December 2019: A year of change, *PV Magazine*, 2019.
   <https://www.pv-magazine.com/module-price-index/>,
   Accessed Dec 29, 2019.

[83] "Dyson sphere" *Wikipedia: The Free Encyclopedia*. Wikimedia Foundation, 1 Nov. 2016.
   <https://en.wikipedia.org/wiki/Dyson_sphere>.

[84] Tsiolkovski, K. and M K. Tikhonravov, M.K., *Works on Rocket Technology*, National Aeronautics and Space Administration, Washington, D.C., 1965.

[85] O’Neill, G.K. and Reynolds, G., Habitats in Space, *The Science Teacher*, 44(6), p. 22-26, 1977.

[86] O’Neill, G.K., The Colonization of Space, *Physics Today*, 27(9) p. 32-40, 1974.

[87] Pitjeva, E.V., High-precision ephemerides of planets—EPM and determination of some astronomical constants, *Solar System Research* 39(3), p.176–186, (2005).

[88] Binzel, R.P., Gehrels, T. and Matthews, M.S., *Asteroids II*. Tucson: University of Arizona Press, 1989.

[89] Al Conrad, P. I., Adamkovics, M., Kleer K., Males, J.R., Morzinski, K.M., Close, L., Kaasalainen, M., Viikinkoski, M., Timerson, B., Reddy, V., Magri, C., Nolan, M.C., Howell, E.S., Benner, L., Giorgini, J.D., Warner, B.D and Harris, A.W., Radar Observations and Shape Model of Asteroid 16 Psyche, *Icarus*, 281, p.388-403, 2017.

[90] Blondel, P., Mason, J., *Solar System Update*, Springer-Verlag, Berlin, 2006.

[91] Pitjeva, E.V., Pitjev, N.P., Mass of the Kuiper belt, *Celestial Mechanics and Dynamical Astronomy*, 130(9), 2018.

[92] Smith, P.C., *Cruise Ships the Small Scale Fleet: A Visual Showcase*, Pen and Sword, Havertown, 2014.

[93] Lide, D. R., Editor, *CRC Handbook of Chemistry and Physics*, 84th Edition, CRC Press, Boca Raton, Florida, 2003.

[94] Lewis, J.S. *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, Addison-Wesley Publishing Co, Reading, Mass, 1996.

[95] Kardashev, N. S., Transmission of information by extraterrestrial civilizations, *Soviet Astronomy*, 8(2), Sept-Oct, 1964.

[96] Smil, V., *Energy and Civilization: A History*, The MIT Press, Cambridge, MA, 2017.
[97] Redding, A.C., *Elon Musk: A Mission to Save the World*, Solon, Ohio : Findaway World, LLC, 2019.

[98] Davenport, C., *The Space Barons: Elon Musk, Jeff Bezos, and the Quest to Colonize the Cosmos*, New York : PublicAffairs, 2019.

[99] Vance, A., *Elon Musk: How the Billionaire Ceo of Spacex and Tesla Is Shaping Our Future*, HarperCollins Publishers, NY, NY, 2016.

[100] Joseph, F., *The Lost Colonies of Ancient America: A Comprehensive Guide to the Pre-Columbian Visitors Who Really Discovered America*, New Page Books, Pompton Plains, New Jersey, 2014.

[101] Medina, N., *Who Was Leif Erikson?*, Penguin Young Readers Group, 2018.

[102] Irving, Wa., *The Life and Voyages of Christopher Columbus*, Ware: Wordsworth Editions, 2008.