Photovoltaics – a Path to Sustainable Futures

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Abstract

As both population and energy use per capita increase, modern society is approaching physical limits to its continued fossil fuel consumption. The immediate limits are set by the planet's ability to adapt to a changing atmospheric chemical composition, not the availability of resources. In order for a future society to be sustainable while operating at or above our current standard of living a shift away from carbon based energy sources must occur. An overview of the current state of active solar (photovoltaic) energy technology is provided here to outline a partial solution for the environmental problems caused by accelerating global energy expenditure. The technical, social, and economic benefits and limitations of photovoltaic technologies to provide electricity in both off-grid and on-grid applications is critically analyzed in the context of this shift in energy sources. It is shown that photovoltaic electrical production is a technologically feasible, economically viable, environmentally benign, sustainable, and socially equitable solution to society's future energy requirements.

Keywords: energy, power, solar, photovoltaic

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Introduction

Although global fossil fuel resources have not yet been exhausted, the negative social, health, and environmental impacts of our current unsustainable patterns of energy use are apparent [1,2,3,4,5]. In the future, large-scale alternative methods of producing the vast quantities of energy needed to sustain and enhance our standard of living are necessary [6,7,8]. As Peter Harper proposed, the problem of contemporary society can be stated succinctly: "We need to get (probably) 11 billion people through the transition complex to 'Sustainia', the sustainable state, before irreversible damage is done" [9]. If current trends continue, future society will require increased electrical energy. This energy must be produced using sustainable technologies in order for society to continue to prosper indefinitely. Fortunately, advances in science and technology have provided us with several alternative means of producing energy on a sustainable level, such as wind, geothermal, biomass, and solar [10]. Of these means, solar (photovoltaic technology) provides the most widely adaptable applications and converts sunlight directly into electrical energy with the highest efficiencies [11,12]. This paper will demonstrate

that photovoltaic (PV) electrical production is a technically feasible, economically viable, environmentally benign, sustainable, and socially equitable solution to modern society's energy requirements.

Overview

Since the beginning of the 1990's the public has slowly accepted that there is a link between global warming and carbon dioxide (CO_2) concentration despite an information war between climate scientists and the fossil fuel industry. The global mean surface temperatures have increased 0.6-1.2°F since the late 19th century while the atmospheric CO_2 concentration has increased by more than 30% to the highest level in 160,000 years [1,7,13,14]. In 1995, the Intergovernmental Panel on Climate Change (IPCC) made up of over 2,500 scientists representing more than 80 countries undertook a review of the current state of climate change science (views presented in the report stem from the analysis of over 20,000 articles from the relevant literature) [15]. More recently the IPCC updated their prediction to state that globally average surface air temperatures is projected to warm by 1.4 to 5.8°C by 2100 (relative to 1990), and globally averaged seal level is projected to rise 0.09 to 0.88 meters over the same time [16]. It is now quite clear that certain gases, such as CO_2, play a crucial role in determining the earth's climate. These 'greenhouse' gases increase the average global temperature by allowing the transmission of solar energy as visible light, which is then absorbed by the earth and re-radiated and trapped as heat. This heat is prevented from escaping into space by these same gases in the atmosphere following the same principle that governs greenhouses or the passenger compartment of a car left in the sun. Researchers have also documented that the increased concentration of such gases in the atmosphere resulted from human activities, predominantly the burning of fossil fuels [15]. It is therefore astute to reduce the burning of these fossil fuels as much as possible to limit the effects of global climate change via emissions of CO_2.

Several international summits convened specifically to reduce the emissions of heat-trapping gases because of the adverse consequences of human induced climate change. In December 1997, at the international Climate Summit in Kyoto, Japan, nations agreed to reduce greenhouse gas emissions by an average of five percent from 1990 levels between the year of 2008 and 2012. Under the accord, the United States will lower the emissions by 7%, Japan by 6%, and the European Union countries by 8% [17]. Largely ignored, is that even if the Kyoto goals are met (which appears extremely unlikely), reductions in atmospheric CO_2 would be an entire order of magnitude below those necessary to stabilize the global climate (atmospheric scientists generally agree that 60-70% reductions would be needed) [18]. Despite their limitations, these internationally backed environmental imperatives have become a driving force behind the development and utilization of PV solar energy, which does not contribute to greenhouse gas emissions during their use.

Individual countries have also made a large drive for PV development by sponsoring progressive energy subsidies for photovoltaics. In Japan, where approximately half of the world's 200MW production (as of 1999) of PV is used[1], a recent subsidy for residential systems resulted in the cumulative number of systems climbing over 34,000 [19]. Because of the huge consumer interest, Japan decreased its subsidy from 50% (1997) to 35% (fiscal year 1999), yet

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[1] The energy units used throughout will be in watts (W) and the power units in watt-hours (W-hrs) where k is 10^3, M is 10^6 watts, and G is 10^9 respectively.

between April 1999 and March 2000 over 17,000 systems were applied for [20]. The European Commission has increased its expenditures to 547 million Euro in order to reach their target goals of 0.075GW installed by 2003 and 3GW installed by 2010 [21]. The stand-out European PV program is the German 100,000 Roofs program – which is a ten year interest free loan. That, combined with their price-incentive program, buying PV in Germany is fully economical [20] now. The United States is also trying to create a solar energy option. In 2000, the Department of Energy spent $17 million for cost-shared PV projects and that will increase to $19 million in 2001 [22]. By far the most ambitious U.S. government program is the Million Solar Roofs Initiative, which will enable businesses and communities to install solar systems on one million rooftops across the United States by 2010 [23]. The million solar roofs project, on target in 1999 (nearly 0.3MW of mostly grid connect schools) and 2000, and looks to be on target for installed capacity in 2001 [22]. Individual states are also contributing to the promotion of solar power. California instituted a buy down program ($3.00/Wp subsidy)[2] that resulted in 200 PV systems in the 2-4kW range being installed [20]. The U.S. government is also continuing to support research into PV, investing ~$76.7 million in 2001 [22].

On a national scale, the rationale for promoting the adoption of PV technology is that PV is critical to energy security, strategic technology, and long-term economic growth [21]. As a distributed generation source, this technology acts as a network (much like the internet), and unlike the conventional grid. It is therefore much less susceptible to large-scale power outages caused by natural (e.g. floods, storms, etc.) or manmade disasters (e.g. terrorism, warfare, etc.). Solar energy also mitigates dependence on foreign energy supplies and thus reduces the need for military action. Finally, it provides benefits for domestic the economies due to the relative labor-intensive [24] nature of the PV industry and the elimination of energy commodity imports [25].

Feasibility: Resource and Technical Limitations

Unlike the current methods that produce the majority of electrical energy, PV is a renewable resource. Thus, PV will continue to produce power indefinitely (as long as the sun shines). Contrary to popular perceptions, with current conversion efficiencies there is more than enough sunlight to easily provide global energy needs both now and in the future. There is a commonly held misconception that sustainable energy via solar cells comes at the price of large surface areas in selected regions [26]. This is simply untrue. The total solar radiation falling on the earth is 1.2×10^{14}kW, which is roughly 10,000 times current world consumption [27]. It would not even be necessary to cover an appreciable area of the planet with PV to provide for current world power from current solar cells (which are generally ~10% efficient). The fossil fuel production of the entire planet could be replaced by hydrogen generated by photovoltaic arrays on an estimated 53 million hectares of arid land (less than 2% of the area of the world's deserts) [25]. In the U.S. the estimations are comparatively bright. The U.S. average solar input is 1,825 kW-hr/m^{2} per year [28]. Even with cells of only 5% efficiency[3], PV could easily provide all of the U.S.'s electrical needs without encroaching on arable land or sequestering panels in the desert. Ideally, solar panels would be located near the consumer in order to eliminate

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[2] The Wp unit represents a measure of the peak power in watts that a solar cell outputs under 1 sun illumination.
[3] PV panels are now only fabricated with such low efficiencies when used for ornamental reasons (e.g. as a replacement for architectural glazing).

transmission losses[4] and limiting support structure costs. This is accomplished by placing solar panels on, or building them into: roofs, building facades, carports, highway sound barriers, etc. Any surface that is exposed to sunlight is a potential location for PV. Thus, an inconsequential area covered by standard solar cells could easily provide the electrical needs of modern society.

Photovoltaic energy production is not a complete solution to all of society's energy requirements, however. PV is hampered my several disadvantages due to its physical nature, namely solar cells only produce energy when illuminated. Thus, to ensure power availability at night solar energy would be produced in excess during the day and stored for use at night. Currently, batteries are most commonly used to store this energy. The major disadvantage of batteries is the added initial capital investment and the greatly augmented upkeep. Solar cells themselves are solid-state devices with no moving parts and thus have negligible upkeep once installed. In a typical home PV/battery system the most economical batteries need to be replaced after ~5 years – thus, also greatly increasing the cost of production for an installed system. Homes with access to the grid could eliminate the need for batteries by inverting their solar energy from DC to AC and supplying excess energy onto the grid. In this way the grid effectively works as a storage medium. It is also possible to couple solar power generating facilities with other conventional sources. For instance, the World Bank recently funded a project that increased the power production of a hydroelectric power plant by adding arrays of solar modules [29]. The solar modules produce power during the day with the hydro plant holding the water in reserve until the night, when it takes over power production. Using similar methods society could double the generation capacity of its current energy plants without increasing environmental damage due to damming additional rivers or emitting more CO_2. As an added advantage to using solar for symbiotic energy production, when electrical demand is highest for many electrical suppliers (during the summer for air conditioning) PV power output is at or near its peak.   Thus solar power facilities can be used to mitigate peak demand and thus hold down costs for current energy suppliers.

Although select regions of the earth's surface that are exposed to higher solar fluxes, are optimal locations for PV arrays this does not preclude the use of solar cells in non-optimal locations. There are lightly inhabited regions where solar energy production is not viable (such as Northern Alaska) due to long periods of deficient sunlight. However, PV is viable in many locations normally perceived as inhospitable to solar technology [30]. The average yearly solar flux for Maine is ½ that of New Mexico. Thus, although a solar array located in New Mexico can produce twice as much energy as an identical array in Maine, solar cells can still be used to generate the necessary energy in the areas available.

Economic Viability

Although solar energy production only commands a small part of the energy pie its slice is rapidly increasing as the price per peak Watt continues to decrease. The world market for photovoltaics exceeded 200MW in 1999, and 260MW were delivered in 2000 [20]. Shipments increased by 52% in the U.S. [31] and 63% in Japan [20]. The increases in shipments in 1999 were partially due to the Y2K hysteria but also the large export market (75% of U.S. whole [31]), which was driven by an increase in subsidies in Japan and Europe (most notably Germany). This remarkable increase in solar energy use was a huge boost to PV manufacturers. To guide it

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[4] Transmission losses can be higher than 50% on antiquated grid lines.

through these increases the U.S. photovoltaics industry designed a roadmap based on a similar roadmap used for the semiconductor microelectronics industry. The conservative annual growth rate of 25% estimated by the PV industry was relatively minuscule compared to the reality of the market. The roadmap predicted that by 2020 the U.S. PV industry will be shipping 6 GWp/yr (3.2 GWp/yr for domestic use) and thus have cumulatively installed ~87 GWp [32]. These rather large numbers must be kept in perspective - the U.S. peak electrical generation capacity in 1999 was ~776 GWp [33] and will likely grow by 2020. The transition to PV power production has only just begun.

A frequent critique of the PV industry is that it can not survive on a level-economic playing field – that it needs subsidies in order to survive. This critique is baseless when considered in the context of the massive public subsidies for the energy industry as a whole. Fossil fuels and nuclear energy receive 90% of U.S. government money, which comes to $43.3 billion (with PV receiving only 3%) [34]. This figure does not include the hidden costs that society subsidizes for the energy industry which include: health impacts (at least $40 billion annually), military (U.S. military spends between $14.6 and $54 billion/yr just defending the oil supplies in the Persian Gulf), employment, crop loss, corrosion, and global warming [34]. In the ideal world on a level playing field, PV would be by far an economically superior energy source.

In the real world, if PV technology is going to succeed, it must become economically competitive in the current subsidized market. PV will accomplish this with economy of scale. As the production volume of solar cells increases the price per module falls rapidly, just as the price of computers plummeted from million of dollars to only several hundred when in mass production. This trend is already apparent from 1975 to the present. The past two decades have seen a sustained price reduction of 7.5%/yr during which the average worldwide production of modules increased by 18%/yr [12]. In order to take advantages of economy of scale and to directly compete with fossil fuel as an energy source, it is generally agreed that 100 MWp PV plants must be constructed [29,35,36]. For PV modules produced at a 100 MWp plant once financing, capital equipment costs, direct and indirect manufacturing costs, installation, power conditioning, operation and maintenance costs, and tax benefits are all taken into account, the installed PV price is likely to fall under $3.00/Wp(AC) [36]. This price makes solar cells economically attractive to a substantial portion of the United States' domestic energy market ~8,000 MWp [36]. The enormous market generated from the relatively small initial investment of $140 million for a 100 MWp/yr plant has obvious implications for energy policy. A 100 MWp/yr power plant is within reach of our current technology and is expected in the near future because once a single 100 MWp/yr power plant is constructed the market will demand 80 others identical to it. As multiple 100MWp/yr plants are constructed the price of solar cells will continue to drop, opening the market to solar power generation even further.

The higher cost of power outside of the United States makes photovoltaic electrical production even more attractive, so large scale mass production of solar cells will be seen first outside of the U.S. N. Mori, the executive managing director of the Photovoltaic Power Generation Technology Research Association, predicts that Japan will begin producing 100 MWp/yr factories between 2003 and 2004 [19]. Thus, the world PV market is finally at the point where it has begun making the transition from the highly subsidized, grid connected market to the fully economic market.

This transition will not disrupt the global economy or catalyze job loss. Opposing popular belief, use of photovoltaic technology actually leads to more jobs than it eliminates. Although, PV once installed is virtually maintenance free and thus devoid of employment for energy production, its fabrication and installation is extremely labor intensive. Thus, investment in solar energy produces substantially higher levels of employment than equivalent levels of investments in conventional energy supplies. A 1997 Pembina Institute report found that for every million dollars invested, an average of 12.2 jobs are created in the renewable energy sector (with PV being the most labor intensive resulting in the creation of 17 jobs). On the other hand, for every million dollars invested in conventional energy, an average of only 7.3 jobs are created [24]. It is predicted that by 2010, approximately 70,000 new jobs could be created as a result of the increased demand for photovoltaic, solar hot water, and related solar energy systems through the installation of one million solar energy systems [37] representing only ~3% of total U.S. energy production. The solar employment/energy ratio compares favorably to the relatively sparse job prospects of the coal industry that only employees ~80,000 to produce about ~1/3 of the energy in the U.S.

Environmental Impacts and Sustainability

Photovoltaics are truly a sustainable and environmentally friendly method of producing energy. PV produces no atmospheric emissions or radioactive waste during use. Therefore, when it replaces fossil fuel energy production it curtails air pollution, which produces acid rain, soil damage, and human respiratory ailments. PV electrical production also discharges no greenhouse gases, such as CO_2, so it will help offset emissions that contribute to global warming.

Contrary to popular perceptions (even espoused by some misinformed environmentalists) solar photovoltaic modules are net energy producers. The myth that photovoltaics demand more energy to fabricate that they produce over their lifetime was refuted as early as 1978 [38]. That study was a limited life cycle analysis (LCA), which only considered the energy to fabricate the PV modules themselves. More detailed studies looked at different geographical locations and found the energy payback period ranged from 7.4 years (Detroit with frame) to 1.2 years (Phoenix without frame) [39]. Further studies compared PV made either from different materials or with different processes and found that crystalline silicon (c-Si) solar cells would pay for themselves in terms of energy in 11.8 to3.3 years, polycrystalline silicon (p-Si) solar cells in 2.4 to 1.5 years, and amorphous silicon (a-Si) solar cells in 2.1 to 1.1 years for a range of theoretical production facility outputs [40]. These analyses were made even more complete by Frankel et al. when they reported a complete LCA for both a power plant and several built in PV installations (1998). They included the balance of systems (BOS), materials, and module energy consumptions for grid connected homes. Using the average Italian solar flux of 1700kW-hrs/m² they found the energy payback times to range from 3 years (PV plant) to 1.5 years (PV integrated roof home) [41]. Next, Alsema finished a meta-analysis of the literature and found the energy payback periods to range from 4 to 2.6 years depending on the application and type of solar cell materials used [42]. With respect to the near-future poly-Silicon (poly-Si) and a-Si PV modules, the energy pay back time was estimated at approximately 2 years or less. In the case of a 10MWp/year annual module production scale a-Si and poly-Si was less than that of c-Si even if the energy content of the off grade Si is ignored [43] (note: presently BP-Solar is up to 8MWp/yr in their amorphous silicon solar cell plant [44]). It is noteworthy that a-Si PV modules are able to

recover the energy input in only a single year when the production scale reaches 100MWp/year [43] (probably in 3-5 years [19]).

The apparent discrepancies caused by the energy payback periods would be expected of complete LCA studies. An LCA can never produce one simple result. The results are ranges of figures showing quantities of energy or materials used and waste generated. Any comparison between solar cells or the processes which produce them must clearly state both the stages the particular study evaluates and the assumptions made for which values could not be found. Ideally a complete life cycle analysis of a PV installation would include: material production energy, manufacturing energy of both the balance of system and the modules, energy use requirements, energy generation, end of use (disposal) energy, and the distribution/transportation energies in between each stage. Each stage of the life-cycle can then be organized into a product, process, and distribution component [45]. The product component of a PV system consists of materials incorporated into the PV module (such as stainless steel and ethylene-vinyl acetate (EVA) in the case of United Solar a-Si PV panels [39] or glass and EVA for BP-Solar a-Si panels in addition to the frame and semiconductor materials). These materials must be followed from the raw material acquisition through to the end-of-life management. The process component includes all fabrication and assembly steps and manufacturing facilities and equipment (this is generally the most straight forward stage to quantify because actual readings can be made during fabrication and the exact inputs and outputs can be determined for any given plant). Finally, the distribution component includes any packaging and transportation necessary to transfer the product materials between stages in the life-cycle. This is where a life-cycle analysis is most qualitative because it depends on variables such as distance to user, mode of transport (usually there would be several), where the panels are located geographically, type of disposal (mechanical separation of glass and roof construction materials from cells and plastic [46], primary recycling of frame or secondary, recycling of glass or dumping, and disposal of remaining materials in a high-active chemical landfill or possible reclamation of electronic materials) and users distance from disposal facility 20+ years in the future, etc. In addition energy pay-back studies generally only analyze the panels themselves but also should evaluate the balance of system (BOS) energy costs: mounting, storage (such as batteries), tie-lines, inverters, charge controllers, etc. Kato et al. calculated the BOS and installation to be about 13% of the whole including an integrated frame, electric components, inverter, and installation [47] for a grid tied system. This value can be used to obtain realistic values of energy payback for complete PV systems from only module values. This is also only a qualitative estimate for a typical PV system- each installation would be slightly different.

No life cycle analysis study has been undertaken to look at all the variables in energy payback for a generic photovoltaic system simply because they are different depending on each application. The bottom line, however, is that PV produce far more energy than they use in their manufacture. The energy pay-back time for a typical 5kWp residential PV system (enough to power a large sized home) is conservatively less than five years which is much shorter than the expected lifetime, usually given as 20 years (but it should be noted that there is no physical reason that a solid state device such as a PV panel should ever fail from use – so the effective lifetime should be considered much longer than 20 years). Thus, because a PV panel produces far more energy over its lifetime than needed to produce it, PV represents a sustainable energy technology.

The positive environmental impacts of PV are clearly illustrated with the same 5kWp photovoltaic system that could be placed on the roof of any typical home. Over a single year, this solar energy array would prevent: 3.3 tons of coal from being burned, 8.5 tons of CO_2 from enhancing the greenhouse effect, ~50 pounds each of NO_x and SO_2 from polluting the atmosphere and causing acid rain, 2.5 pounds of particulates from causing a health hazard, 571 pounds of ash from being disposed of in landfills, and conserve over 5,000 gallons of water[5]. A typical solar cell has a 20-25 year official lifetime[6] and thus the propensity for incredible pollution mitigation.

Photovoltaic technology is obviously an enormous environmental benefit. It represents a sustainable solution to our current energy requirements because the active material making up the majority of PV cells is silicon, which is readily available in sand. Also, the abundant energy a single PV generates over its lifetime could be used to produce more PV identical to it. Thus PV is a true breeding technology – it can reproduce itself sustainably over time while providing for society's energy needs.

Social Consequences of Converting to Solar Power

In stark contrast to the energy sources of the past, active solar technology has a plethora of positive social consequences and could even assist in increasing social equity. Photovoltaic energy production will benefit global society by creating jobs, distributing energy supplies, and preventing pollution that results in health, and environmental degradation.

Photovoltaic energy production can assist individual self-reliance. By the very nature of photovoltaic technology it is a distributed energy system. Thus, the energy can be generated where it is consumed, and thus does not have to rely on a grid (known to have frequent power failures). The consumer also avoids being coerced into purchasing power from a supplier. This ability to produce one's own power allows for greater personal freedom while preserving all the amenities of modern life.

Being that PV is truly a universal power source (almost everyone has access to the sun) this technology has the propensity to be an equalizing factor in wealth disparity between both rich and poor countries but also rich and poor individuals. As compared to developed countries, developing countries possess a strategic advantage for adopting PV because of their much lower technological inertia. They posses a much lower level of commitment to fossil fuel technologies in terms of infrastructures, capital vintages, employment skills, management organization, and political institutions. The developing countries could effectively 'leap frog' antiquated energy technologies rather than follow exactly in the historical path of developed nations. However, it should be noted, that any form of electrical energy is prohibitively expensive for the average citizens of developing nations. In developed nations, the current high price of home-based PV systems is also prohibitive to most homeowners. Thus, only upper or upper-middle class individuals have purchased PV systems. However, as prices continue to plummet with rising production volume the cost of a PV system is entering the price range of middle and lower class citizens. Already PV has found a niche market in mobile campers. This vanguard of PV owners will help acclimate the general public to the use of PV. This growing familiarity and the

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[5] Calculations are based on data from a 500MW Coal fired power plant and assuming 1600 peak hrs/yr. [48]
[6] Theoretically solid-state devices like PV cells and solid-state lasers should continue to function indefinitely. In fact, the first silicon solar cells are still in operation today.

independence from paying electrical utility bills every month alone is a strong incentive for individuals to convert their homes to solar power electrical generations stations.

The benefit of PV power generation to the health of current population but more importantly for future generations is clear. Due to the offset of air pollution (NO_X, SO_2, and particulate emissions) from coal produced electricity there are immediate health benefits such as reduction in premature mortality from respiratory disease and chronic bronchitis. Reduction in air pollutants also helps less serious maladies like reduction of asthma symptoms, acute lower respiratory symptoms, and restricted activity days (days in the hospital) [49].

Conclusion

Solar photovoltaic technology provides a technologically feasible solution to societies current health and environmental dilemmas posed by the reliance on fossil fuel based power generation. Solar energy is already economically viable in many applications, and will continue to expand as production continues to increase in scale. Economics of scale will decrease the cost of solar energy while simultaneously facilitating net job creation. PV will not only enhance social equity by creating jobs, but as a distributed energy source it will enable individuals to be more self-reliant without forsaking modern conveniences and technology. In addition, photovoltaic energy production represents an environmentally beneficial and sustainable method of maintaining an energy intensive standard of living, which will enable development without compromising those who will live in the future to do the same.

Acknowledgements

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Vitae

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