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INCREASING PV VELOCITY BY REINVESTING THE NUCLEAR ENERGY INSURANCE SUBSIDY IN LARGE-SCALE PHOTOVOLTAIC PRODUCTION

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ABSTRACT

As the debate over the future of energy grows, often nuclear energy production is pitted against solar photovoltaic energy conversion. There is a widespread belief that solar cannot compete with nuclear energy economically without government subsidies. The continued and widespread belief in the economic viability of nuclear energy, however, is predicated in part on government-mandated limitation on the liability of the nuclear industry. To demonstrate the magnitude of this nuclear energy insurance subsidy, this paper considers a shift in policy to reinvest only the premiums of the nuclear energy insurance subsidy into large scale solar photovoltaic production. The current insurance subsidy for a single nuclear power plant in the U.S. is reviewed along with the investment requirements for a one GigaWatt thin film amorphous silicon solar photovoltaic manufacturing plant. The available power and energy are then compared for an ensemble of nuclear power plants and solar photovoltaic arrays produced by the manufacturing plants over a nuclear plant life cycle. The startling results show that only the premiums for nuclear energy insurance would result in both more installed power and energy produced by mid-century if these funds were invested in large scale photovoltaic manufacturing. This study clearly shows that policies to transfer the nuclear energy insurance subsidy to large-scale manufacturing would increase the PV velocity to push the PV industry over 1 TW in under fifty years.

INTRODUCTION

The ongoing global climate destabilization resulting from greenhouse gas emissions creates an enormous need for a large-scale source of energy alternatives to fossil fuels [1-3]. As the intense debate over the future of energy grows, often nuclear production is pitted against solar photovoltaic energy [4]. This argument is most acute when considering government subsidies for some replacement of polluting fossil fuels. This article provides insight into this debate by comparing the indirect subsidy of liability limits for the nuclear energy industry to the cost of large-scale photovoltaic manufacturing. The magnitude of the nuclear energy insurance subsidy is reviewed and the results on energy production are determined for a transfer of that subsidy to large scale photovoltaic manufacturing. In order to make this comparison, the current insurance subsidy for a single nuclear power plant in the U.S. is estimated from the few

studies completed in the literature, along with the investment requirements for a one GigaWatt (GW) solar photovoltaic (PV) manufacturing plant. Then the available power and energy are compared for a nuclear power plant (NPP) and a photovoltaic energy ensemble created from the running of the single GW PV manufacturing plants funded with the subsidy transfer.

NUCLEAR ENERGY INSURANCE

Before the first nuclear energy reactor was constructed, insurance agencies were unwilling to provide adequate liability and indemnity for nuclear utilities in the event of a catastrophic nuclear accident, simply because of the sheer magnitude of such a devastating event [5] as it would likely bankrupt any company held responsible. To resolve this problem, in 1957 the U.S. government legislated the Price-Anderson Nuclear Industries Indemnity Act (commonly called the Price-Anderson Act or PAA [6]), which has since been renewed several times (1967, 1977, 1988, 2002, and most recently through 2025 via the Energy Policy Act of 2005). The PAA governs liability-related issues for all the non-military nuclear facilities constructed in the United States before 2026. This act limits the liability of private operators for a nuclear accident by requiring private nuclear power licensees to provide a maximum primary liability of \$300 million. If there were a large accident and claims exceed this primary liability, the Price-Anderson Fund requires all licensees to pay a maximum of \$95.8 million (totaling roughly \$10 billion if all reactors were required to pay the maximum) at the time of the accident. Any liabilities in excess of the \$10 billion cap are covered by the U.S. government. Thus, the nuclear power industry is relieved of any liability beyond the insured amount for any incident involving radiation or radioactive releases regardless of the fault or the cause. Initially, the PAA was intended to be temporary, expiring in 1967 as it was assumed that once the companies had demonstrated a record of safe operation they would be able to obtain insurance in the private market. This did not happen. As former U.S. Vice-President Dick Cheney pointed out in 2001, without the PPA "nobody's going to invest in nuclear power plants" [7]. Even today, it is well established that nuclear power is not insurable in the free market [8] and governments have had to provide some form of limited liability for nuclear utilities for any company to consider building a reactor. Outside of the U.S., the Vienna Convention on Civil Liability for Nuclear Damage (1963)

was also formulated, with a limited liability for individual licensees set at US\$400 million and ratified in 1997. Largely depending on the geographic location of the nuclear power plant, the devastating economic consequences of a catastrophic nuclear accident are in the order of hundreds of billions [9,10]. Thus, the Nuclear Regulatory Commission concluded that the liability limits were sufficiently significant to constitute a "subsidy". However, a quantification of the amount of the subsidy was not attempted [11] and, as shown in the next section, remains remarkably under-investigated. It should be noted that generally in economics, a subsidy is a payment made by the government which forms a wedge between the price consumers pay and the costs incurred by producers, such that the price is less than marginal cost. In this case, because there is no payment unless such a catastrophe occurs, there is no "direct subsidy," although there is an indirect subsidy because no NPP could be built without it. The PAA limit of \$10 billion provides this indirect subsidy to the nuclear industry as it reduces the real insurance premiums paid by nuclear power plant operators. Thus the nuclear industries cost of capital does not reflect the risk of having to pay for damages in excess of \$10 billion, when estimates of worst-case accident or sabotage scenarios are much higher than that [9,10,12]. In the wake of September 11th, the possibility of a disaster involving nuclear energy and costing many times \$10 billion is clearly not as low as it was earlier last century [13]. Here, a shift in policy is considered by a direct transfer of this subsidy to the PV industry.

INSURANCE SUBSIDY FOR NUCLEAR POWER

It is very difficult to directly estimate the value of limited liability for the nuclear industry. Although both the statistical treatment of extreme values and the study of low-probability risks is familiar to many disciplines such as hydrology, climatology, structural and safety engineering, risk analysis, insurance, financial markets and electricity markets [14], it has been applied infrequently to this problem of nuclear liability.

The actual value of the PAA was first estimated by Dubin and Rothwell [15] pre-9/11 in 1990 and no other complete study has been published in the literature since. They developed a method to derive estimates for the amount that nuclear operators would have to pay for off site insurance in the absence of the PAA limits. The technique involves extrapolation from the premiums that operators now pay for the portion of liability that they still bear under Price-Anderson. Their estimates of the size of the subsidy ranged up to \$33 million (2001 dollars) per reactor per year of operation. Heyes and Liston-Heyes reapplied Dubin and Rothwell methodology but corrected the method of interpreting current insurance arrangements, which reduced the estimates of the implicit subsidy by one order of magnitude [16]. This study did not update the risk and as Heyes writes "Do Heyes and Liston-Heyes think that the true number might actually be 10 times bigger? Sure they do." [9]. There is enormous variability in the estimate of the nuclear energy insurance subsidy, which range between 0.5¢ and 30¢ per kilowatt hour (kW-hr) of electricity produced [9,15-18].

This variability is due to a fundamental assumption found in the Dubin and Rothwell methodology [15] (and thus also the work of Heyes and Liston-Heyes [16,17]) that premiums for current risks are set at their "correct" levels because someone knows what the real probability-consequence profile looks like, and has set an actuarially appropriate premium on the basis of that knowledge. This knowledge, of course, does not exist and there have been remarkably few attempts in the academic literature to narrow the uncertainty. Here, in light of Heyes's comments, the figure of \$33 million per reactor- year will be used as the estimate of the value of the PAA. This value certainly has a large uncertainty associated with it, but is used here to provide a baseline for semi-quantitative comparison. No claims are made on the exact value. Clearly, further work is needed in this area.

1 GW SOLAR PHOTOVOLTAIC MANUFACTURING PLANT: INVESTMENT REQUIREMENTS

The learning curve established by the PV industry over the past 30 years has become the equivalent of Moore's Law in the semiconductor industry. Every doubling of cumulative PV production experience yields a double-digit percentage reduction in the costs of PV modules. Most studies indicate a learning rate for PV modules of approximately 20%. [19-21]. The day that solar electricity reaches grid parity is thus growing rapidly closer for an ever expanding list of geographic locations and utility grids [21]. The rate of solar electric price reductions is accelerating towards grid parity because of the explosion in growth in the industry. The world solar PV market installations surged 110% over the previous year to reach a record high of 5.95 GW in 2008 [22]. Nowhere was this growth more aggressive than in '2nd generation' thin film PV production, which grew by 123% in 2008 to reach 0.89 GW [22]. Growth of thin film PV can be attributed to two types of improvements in the industry. First, improvements of technical knowledge, such as a clear understanding of the nature of polycrystallinity in amorphous, nanocrystalline, and microcrystalline silicon materials and their concomitant solar cells [23,24]. This scientific understanding improves module performance and thus increases the output for a given production line (e.g. more MW/year with the same capital equipment investment). Second, according to VLSI Research a key trend for the last year in the PV industry was the 'rise of the turnkey thin-film line' [25]. These turnkey manufacturing plant (fab) providers, which include in order of market size: Applied Materials, Roth & Rau, Centrotherm, Oerlikon, Ulvac, Manz Automation, Schmid Gruppe, von Ardenne, RENA, and 3S, allow for a multiplication effect in production capacity [26]. The key advantage that provides this multiplication effect to these thin film amorphous silicon based solar cell turnkey solutions is that they are supported by large multinational corporations with established track records of success in both the semiconductor and equipment manufacturing industries. In addition, these turnkey providers often have worldwide support teams and experience supplying turnkey

manufacturing solutions for other industries. This experience and established skill sets reduces ramp up time, allows the rapid spread of technology, best practices, and technology transfer, and greatly expands the PV production rate (velocity) from what could occur with new manufacturing companies starting out on their own. There is considerable literature showing economy of scale improvements with large fabs. With a large fab (GW/yr-size), even a single manufacturing plant of thin film PV can reach grid parity [26,27]. To purchase such a turnkey 1GW/yr thin film solar photovoltaic line costs about \$2/W/yr [28]. In addition, the infrastructure (building, gas supply/handling equipment, land etc.) will add another approximately \$400 million for a total cost of \$2.4 billion [28].

ANALYSIS OF SUBSIDY TRANSFER

Using the data in the previous two sections, a \$33 million/year insurance subsidy for a single reactor would need to accrue 73 years to purchase a 1GW/yr solar photovoltaic fabrication facility for ~\$2.4 billion. Likewise the insurance subsidy for 73 NPPs could provide the capital for a 1GW/yr PV fab in a single year. In order to observe the rapid increase in deployed PV from a 1 GW/yr fabrication facility, here it is assumed that the nuclear insurance subsidy from 73 NPPs is transferred to PV manufacturing in the first year and every year after for the life of the NPPs. This number of new NPPs may at first appear unrealistic, but to make a significant impact in reducing greenhouse gas emissions as energy demand continues to escalate, such rapid increases of NPP deployment is necessary [29]. Thus, making these assumptions, a one GW/yr PV manufacturing line is put in production every year. For simplicity, the cost of money, energy, and inflation are ignored. Over the lifetime of these 73 nuclear power plants, which was estimated at 50 years, this subsidy shift would result in 50 single GW PV fabrications facilities being constructed. If this shift in subsidies were to take place in 2010 the 50 new PV fabs would be fully financed by 2060.

RESULTS

To put the nuclear insurance subsidy figure into perspective, the power and energy available from solar PV can be calculated for transferring the monetary value of that subsidy into large scale photovoltaic fabrication facilities.

The results of such a policy shift are shown in Fig. 1 from 2010 to 2060 (the y-axis is shown logarithmically for clarity). The total cumulative power available for any year for the 73 1GW nuclear power plant ensemble deployed in 2010 is shown in blue squares in Fig. 1. The number of 1 GW/yr PV fabs is shown in red diamonds and increases monotonically by 1 fab per year. The number of deployed PV arrays increases radically because each additional year one new fab goes online and all the fabs constructed in previous years continue to produce 1 GW of PV cells per year. This increase in PV arrays deployed is shown in yellow triangles. To be conservative the peak power available from the PV plant is not counted until the year after financing would be fully

secure. By 2055 more than 1 TerraWatt (TW) of PV will have been deployed. It is also clear from Fig. 1 that in 12 years after the shift (by 2022) the number of installed PV arrays have a peak power equivalent to the 73 single GW NPPs replaced. By the year 2060 in the two scenarios there are or 50 GW of PV fabs and a remarkable 1,275 GW of peak PV power available from the PV arrays produced by those fabs.

Fig. 1 Cumulative power for 73 single GW nuclear power plants, capacity of PV fabs, and the solar photovoltaic arrays from 2010 to 2060 funded by the identical nuclear insurance subsidy of \$2.4 billion/year.

Fig. 1 alone can be somewhat misleading because nuclear power stations have much higher utilization than solar farms. This is because the photovoltaic panels can only generate electricity when they are illuminated. Thus, the time the nuclear and solar plants are in use must be considered. If it is assumed that the NPP is in operation 90% of the time (a reasonable assumption from past performance [30]), allowing for routine maintenance, it produces roughly four times more energy per unit power than a photovoltaic array. To estimate the amount of energy produced by the photovoltaic ensemble, 5 sun hours (or 21% utilization) was chosen for illustrative purposes, thus assuming that the PV arrays would be deployed in favorable geographic locations such as the U.S. southwest.

From these estimations the energy production per year for the 73 single GW NPPs (blue squares) and the PV arrays (red diamonds) was calculated and is shown in Fig. 2 from 2010 to 2060 (not logarithmic scale). Where the two data sets intersect represents the point at which both technologies produce the same amount of energy in that year. This occurs between 2035 and 2036, or roughly 25 years after the shift, as rapid growth of solar electricity overtakes the steady production of the NPPs.

Fig. 2 Energy production per year for 73 1GW nuclear power plants and solar photovoltaic arrays from 2010 to 2060 funded by the identical nuclear insurance subsidy of \$2.4 billion/year.

As can be seen, in Fig. 2, the PV arrays produce far more energy (over 3 times as much in 2060) than the NPPs. However, in the first two and a half decades, the NPPs produce more energy than the PV. To account for these kinetics, the cumulative energy production for the 73 single GW NPPs (blue squares) is plotted against that from the PV arrays (red diamonds) from 2010 to 2060 in Fig. 3.

Fig. 3 Cumulative energy production for 73 single GW nuclear power plants and solar photovoltaic arrays from 2010 to 2060 funded by the identical nuclear insurance subsidy of \$2.4 billion/year.

In the case studied here, it takes the PV arrays some considerable time to surpass the NPPs in total energy produced. Cumulative energy production parity is not reached until between 2053 and 2054 (43 years after the policy shift). For the next six years, however, the exponential rise of the cumulative solar electricity production dwarfs the linear increase for the NPPs. By the end of the 73 NPPs's life they have produced 3.1×10^{13} kW-hrs of electricity compared to the PV arrays' 4.0×10^{13} kW-hrs. It should be noted that this methodology actually underestimates the amount of energy the PV arrays will produce over their life time as solar photovoltaic cells as solid state devices should have very long lifetimes. This means that the additional energy produced by the PV arrays over the artificially short timespan (set by the NPP life) should be regarded as a lower estimate as the PV panels produced in year 2060 would at least continue to produce over their lifetime given by warranty (generally 20-30 years). Thus in 2060 when NPP output drops to zero, that year 50 GW of brand new solar panels would be deployed. Additional analysis could be made using a lifetime for the PV, any reductions in their performance over time, and then both reducing PV energy as PV panels installed early are removed from service and those installed later are allowed to reach their end of life. Again, this will be left for future work. Overall, using the assumptions above, the shift of the nuclear insurance subsidy from nuclear power plants to large scale PV production facilities would result in an additional 9.4×10^{12} kW-hrs by 2060. At the current U.S. national average of electricity rates of \$0.10/kW-hr this amount of energy is worth \$937 billion. This is particularly remarkable when comparing this additional value from PV electricity to the total value of the nuclear insurance subsidy over 50 years for the 73 plants of only \$127 billion. Thus, in this simple analysis, an additional \$937 billion worth of electricity would be generated by PV by 2060 if the nuclear energy subsidy of \$127 billion alone were shifted from 73 NPPs to PV.

These results are somewhat shocking as the value of the nuclear insurance subsidy is normally given very little attention in the academic sphere (as evidenced by the dearth of studies), by the government [10] or in the popular press (most Americans are unaware that the liability for a catastrophic nuclear accident is covered by tax payers and not the private companies profiting from the sale of nuclear electricity). It appears clear that both the long term domestic energy capacity and economic prosperity is retarded by energy policy that favors an insurance subsidy to the nuclear energy industry rather than a direct subsidy to a renewable form of energy such as photovoltaics.

LIMITATIONS

It should be noted that this semi-quantitative study is meant only as a guide to compare policy options and in no way claims definitive numbers for the values of NPP or PV outputs. As noted in the first section there is an enormous range in the literature for the value of the nuclear

insurance subsidy and an up-to-date and robust study clearly has not yet been funded. This study would itself continue to evolve as the estimated costs for the Chernobyl accident continue to mount (e.g. the Ukraine claims to have lost between \$120 and \$130 billion and Belarus over \$35 billion) [31]. This study would also be complicated by the fact that having had a limit placed on liability for the nuclear industry distorts standard methods to quantify risk [32] because standard assumptions about the self-correcting experience in other industries would be voided. In addition, if at any time in the period analyzed there is any kind of substantial nuclear accident, anywhere in the world, the imagined market cost of the insurance for nuclear would increase drastically and therefore the value of the indirect subsidy would also be correspondingly much greater. Even if the most optimistic low values are assumed for the value of the PAA nuclear energy insurance subsidy a substantial amount of PV energy could be produced from a subsidy transfer over time. Again the exact values found here are of less importance than the trends and these trends clearly point to both the need for further investigations of liability values and the need to reevaluate energy policy. In addition to the assumptions surrounding the PAA, other assumptions can have large implications on the final values of energy produced, such as the number of sun hours, which clearly varies depending on the geographic locations in which the PV arrays are deployed. To have more definitive values much more rigorous studies would need to be completed in the future taking into account learning curves, advances in technology for both PV and nuclear energy, lifetimes of panels, deployment logistics, much more fine-tuned risk assessments, inflation, the value of money, and energy price escalations.

CONCLUSIONS

This preliminary study provides a semi-quantitative baseline to compare a single indirect subsidy for the nuclear energy industry to its value in PV production. The surprising results show that only the premiums for full nuclear energy insurance would result in both three times more installed power and an additional 9.4×10^{12} kW-hrs of energy produced by 2060 if these funds were transferred from 73 nuclear power plants and invested in large scale photovoltaic manufacturing. At value of \$0.10/kW-hr the additional energy supplied by the PV arrays funded by a \$2.4 billion/year subsidy is worth \$937 billion after 50 years. This transfer of the nuclear energy subsidy would result in the PV industry climbing over 1TW of installed capacity near mid century. Although, these numbers may vary based on the assumptions this study clearly shows that policies to shift the nuclear energy insurance subsidy to large-scale manufacturing could assist in PV velocity.

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REFERENCES

- [1] M.I., Hoffert, et al., "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet", *Science*, **298**, 2002, pp. 981-987.
- [2] C.F. Kutscher, (editor), *Tackling Climate Change in the U.S. Tackling Climate Change in the U.S. Potential Carbon Emissions Reductions Efficiency and Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030*, American Solar Energy Society, January 2007.
- [3] J. M. Pearce "Photovoltaics – A Path to Sustainable Futures", *Futures* **34**(7), 2002, pp. 663-674.
- [4] K. W. J. Barnham, M. Mazzer, and B. Clive, "Resolving the energy crisis: nuclear or photovoltaics?", *Nature Materials* **5**, 2006, pp. 161 – 164.
- [5] B. McNeil, "The Costs of Introducing Nuclear Power to Australia", *J. of Australian Political Economy* **59**, 2007, pp. 5-29.
- [6] United States General Accounting Office, "Nuclear Regulation: NRC's Liability for Nuclear Power Plants Owned by Limited Liability Companies", *Report to Congressional Requesters*, May 2004.
- [7] Reuters, "Cheney says push needed to boost nuclear power", *Reuters News Service*, May 15, 2001.
- [8] R. Hans-Holger, "Carbon Free Energy", presented at *2nd Canadian Climate Change Technology Conference*, May 13, 2009.
- [9] A. Heyes, "Determining the Price of Price-Anderson", *Regulation*, **25**(4), 2003, pp. 105-110.
- [10] The Chernobyl Forum: 2003–2005, *Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine, 2nd revised version*, IAEA Division of Public Information, IAEA in Austria, April 2006, IAEA/PI/A.87 Rev.2 / 06-09181.
- [11] United States Nuclear Regulatory Commission, *The Price-Anderson Act: the Third Decade*, NUREG-0957 (Washington, DC, 1983).
- [12] P. A. Bradford, "Renewal of the Price Anderson Act", *Testimony before the United States Senate Committee on Environment and Public Works Subcommittee on Transportation, Infrastructure and Nuclear Safety*, January 23, 2002.
- [13] C. Behrens and M. Holt, "Nuclear Power Plants: Vulnerability to Terrorist Attack", *Congressional Research Service, Report for Congress*, Order Code RS21131, Updated August 9, 2005.

- [14] N. E. Hultman, J. G. Koomey, D. M. Kammen, "What History Can Teach Us about the Future Costs of U.S. Nuclear Power", *Environ. Sci. Technol.* **41**(7), 2007, pp. 2087–2094.
- [15] J. A. Dubin, and G. S. Rothwell, "Subsidy to Nuclear-Power through Price-Anderson Liability Limit", *Contemporary Policy Issues*, 8, 1990, pp. 73-79.
- [16] A. G. Heyes and C. Liston-Heyes, "Subsidy to nuclear power through Price-Anderson liability limit: comment", *Contemporary Economic Policy* **16**, 1998, pp. 122–124.
- [17] A. G. Heyes and C. Liston-Heyes, "An empirical analysis of the Nuclear Liability Act (1970) in Canada", *Resource and Energy Economics* **22**, 2000, pp. 91-101.
- [18] D. M. Kammen, and S. Pacca, "Assessing the costs of electricity", *Annual Review of Environment and Resources* **29**, 2004, pp. 301-344.
- [19] G. J. Schaeffer, Seebregts, A.J., Beurskens, L.W.M., Moor, H.H.C., Alsema, E.A, Sark, W., Durstewicz, M., Perrin, M., Boulanger, P., Laukamp, H., Zuccaro, C., "Learning from the Sun; Analysis of the use of experience curves for energy policy purposes-The case of photovoltaic power", *Final report of the Photex project*, 2004 DEGO: ECN-C–04-035.
- [20] L. Neij, "Cost development of future technologies for power generation—a study based on experience curves and complementary bottom-up assessments" *Energy Policy* **36** (6), 2008, pp. 2200–2211.
- [21] M. R. Pinto, "Has the sun finally risen on photovoltaics?," *2008 Symposium on VLSI Technology*, , 2008, pp.2-5.
- [22] Solarbuzz, "Solarbuzz Reports World Solar Photovoltaic Market Grew to 5.95 Gigawatts in 2008", *World PV Industry Report Summary*, Available: <http://www.solarbuzz.com/Marketbuzz2009-intro.htm>
- [23] R. W. Collins, A.S. Ferlauto, G.M. Ferreira, C. Chen, J. Koh, R.J. Koval, Y. Lee, J.M. Pearce, and C. R. Wronski, "Evolution of microstructure and phase in amorphous, protocrystalline, and microcrystalline silicon studied by real time spectroscopic ellipsometry", *Solar Energy Materials and Solar Cells* **78**(1-4), 2003, pp. 143-180.
- [24] A. S. Ferlauto, G. M. Ferreira, R. J. Koval, J. M. Pearce, C. R. Wronski, R. W. Collins, M. M. Al-Jassim, and K. M. Jones, "Evaluation of Compositional Depth Profiles in Mixed Phase (Amorphous + Crystalline) Silicon Films from Real Time Spectroscopic Ellipsometry", *Thin Solid Films* **455-456**, 2004, pp. 665-669.
- [25] VLSI Research Inc. "Photovoltaic Cell manufacturing equipment:Top-10 supplier ranking" 2009. Available https://www.vlsiresearch.com/cms_pdf_upload/pdf_file_1233694471.pdf
- [26] M.S. Keshner and R. Arya, "Study of potential cost reductions resulting from super-large-scale manufacturing of PV modules", *National Renewable Energy Laboratory final subcontract report*, 2004, NREL/SR-520-36846.
- [27] J. M. Pearce, "Industrial Symbiosis for Very Large Scale Photovoltaic Manufacturing", *Renewable Energy* **33**, 2008, pp. 1101-1108.
- [28] H. Weinzerl, Oerlikon Solar Americas, Oerlikon Solar USA, Inc. Personal Communication, Jan 18, 2009.
- [29] J.M. Pearce, "Thermodynamic Limitations to Nuclear Energy Deployment as a Greenhouse Gas Mitigation Technology", *International Journal of Nuclear Governance, Economy and Ecology* **2**(1), 2008, pp. 113-130.
- [30] Energy Information Administration, "Table 8.1 Nuclear Energy Overview" *Energy Information Administration/Monthly Energy Review*, April 2009, p. 113.
- [31] BBC News, "Neighbours count cost of Chernobyl disaster", *BBC News*, Sunday, 26 April, 1998,
- [32] H.D. Sharma (editor), *Energy Alternatives: Benefits and Risks*, Institute for Risk Research, University of Waterloo Press, 1990.