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The PV Efficiency vs R&D Effort Learning Curve for Research-Stage Material Technologies

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***Abstract* — The trajectory of PV technologies are frequently presented and discussed in terms of record efficiency versus date, or for commercialized technologies, also in terms of learning curves showing cost or price versus total number of modules. For early-stage PV material technologies, efficiencies are typically low and of course no modules have been produced. We introduce a different learning curve appropriate for assessing the trajectories of PV technologies still in the R & D stage; efficiency as function of total publications which aims to capure total R&D effort for each technology. The premise was that material technologies that were intrinsically better for PV should give more efficiency for lower total effort. Incredibly, the trajectories of many major single-junction cell technologies – Si, CIGSe, CdTe, and halide perovskites – all follow the same curve. The curve is logarithmic, capturing the common-sense idea that each limiting problem for a PV technology is harder than the last (diminishing returns). We present the trajectories of many common single-junction technologies and discuss insights gained from analyzing their trajectories through this different lens. We present this learning curve and give our own discussions and speculations on factors affecting trajectories and implications from the analysis. We hope to spark interesting discussions and further analyses by presenting the work.**

Recently, we completed our analysis of the R&D trajectories of different PV material technologies on a plot of record efficiency versus logarithm of number of research publications [1]. This effort was premised on the desire to come up with a method for identifying and assessing promising new PV materials while they were still in their infancy, that is before many papers had been published and before real-world-useful efficiencies had been reached. We noticed that plots of efficiency vs time, while excellent for showing the grand sweep of PV technology development, do not capture the effort put into each technology or the size of the research community dedicated to each. Ideally, we would have data on total person-hours and total budget spent on each technology and the causal relationships of effort leading to both efficiency breakthroguhs and incremental increases. However, since this data is not available, we chose to use publications as a proxy for those variables. The result was Figure 1 reproduced herein. The concept was that an ideal PV material should yield higher effiency for less effort.

Intriguingly, we found that Si, CdTe, CIGSe, and the halide perovskites all seem to follow a common trajectory of 5% absolute efficiency per 10x more papers and reaching 20-24% within 10,000 or fewer papers. This trend holds over 3-4 orders of magnitude of number of papers. We were surprised to find that the near-commercial halide perovskite technology, despite its metoric rise on the NREL chart of effency vs time, followed the same learning curve – that is nearly the same amount of total research effort is correlated with efficiency as for other high-efficinecy technologies.

One of our unproven speculations is that the logarithmic dependence of efficiency vs papers ultimately stems from the physics of efficiency; that ultimately the technological trajectory is limited by increases in V_{oc}, which scales as logarithm of external radiative efficiency. That is, how closely the optical and electrical designs asymptotically approach perfection.

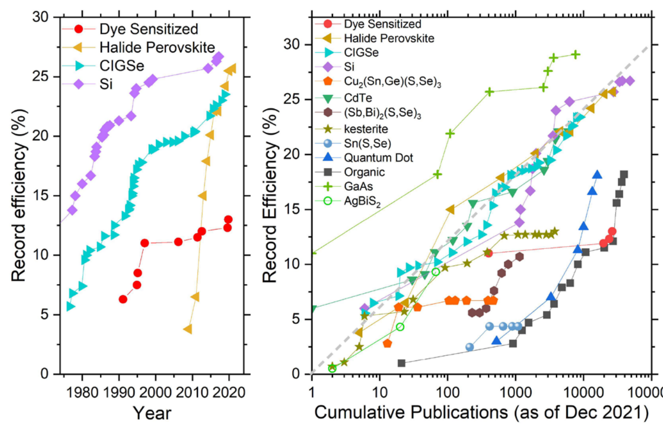

Figure 1 – (right) Efficiency vs. year for representative PV material technologies. (left) Efficiency vs number of publicaitons on log scale.

We point out some predictable factors that will not be captured by this analysis; hidden commercial effort, cross-pollination, and spillover. Record efficiencies may be set by academically-publishing research entities, or by non-publishing commercial entities (especially, but not always, as the technology becomes more mature and heads towards commercialization). Cross-pollination encompasses the transfer of concepts, techniques, and tools from one PV technology to another. For examples, CZTS benefitted heavily from the experience and infrastructure of CIGSe researchers and halide perovskites from those of organic and dye-sensitized cells. Spillover refers to tech transfer from non-PV applications into PV; Si and GaAs benefit from the enormous electronics and optoelectronics industries, while some material technologies like CIGSe are solely used in PV. We hope that ofurther discussions will illuminate and investigate other factors and add understanding of factors affecting these trajectories.

We point out that these technological trajectories are correlations and do not capture causation. From this coarse analysis, we can not resolve questions such as whether technological progress should be viewed as being driven by the entire publishing community, or by only a small group of leaders and seminal papers. We speculate that both the probabilities of breakthroughs and incremental progress scale with the number of people working on a material and the resources brought to bear.

Since we could show that the learning rate for commercial technologies at all stages of development increases logarithmically by 5% absolute per order of magnitude this allows a benchmarking of new materials to see how they compare. Our original analysis investigated the behaviour of 13 material systems and excluded several systems including antimony seleno-sulfoiodide, zinc phosphide, and non-halide containing perovskites. Additionally, we restricted ourselves to single junction technologies, however the rate of progess of tandem photovoltaic devices is of interest. Therefore we will analyse previous historic efficiency data to elucidate the learning curves of the previously unstudied materials as well as tandem devices.

References

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