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From 1e-4 m² to 2e+4 m² and Beyond: The Long Road from Lab to Manufacturing

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Abstract: So just how, exactly, does one take something that works in a lab and turn it into a mass produced, globally marketed product? What could be done better to make the whole process more efficient at delivering 'lab marvel' into 'everyday utility'? What are the skill-sets of the people who do this kind of manufacturing development? How are those skill-sets complementary to and synergistic with the skills of scientists in academia? What is the best marriage of these diverse kinds of people to deliver results quickly and consistently? This article will discuss the steps from lab to manufacturing and the pitfalls and opportunities that can make the difference between success and failure.

Keywords: Dye-sensitized cell (DSC) · Lab · Manufacturing · Prototype · Scale-up

Introduction

So just how, exactly, does one take something that works in a lab and turn it into a mass-produced, globally marketed product? What are the actual steps made behind the mysterious closed doors of 'industry'? What could be done better to make the whole process more efficient at delivering 'lab marvel' into 'everyday utility'? What are the skill-sets of the people who do this kind of manufacturing development? How are those skill-sets complementary to and synergistic with the skills of scientists in academia? What is the best marriage of these diverse kinds of people to deliver results quickly and consistently?

Why this Article

It is not often that those worker drones in industry stand back and take stock of what they do. They are simply too busy to take the time for something like that – even though a pause to smell the roses every so often would give the benefit of perspective.

The same is true in academia and in the labs at university where scientists are immersed in the esoterica of redox couples and the electrochemistry of corrosion. Who needs to stop and think about life beyond the lab? Besides, once it is working in the lab, isn't the rest easy? Don't you just make more of it and faster? Somebody has to think about the best way to make the journey from tiny lab cells to working photovoltaic products, and this article will try to capture some aspects of that process. The intended audience includes those in academia who are contemplating commercializing their discovery, those entrepreneurs who have read about a new lab discovery, and anyone who is considering whether such a life commitment is really what he or she wants to do someday. This article is just the tiniest window into the world of start-ups and commercialization of new discoveries. Only one in ten start-ups succeed, so there is substantial risk in the venture. The best advice in this article is to seek the best advice possible from experienced and seasoned veterans of previous start-ups – even, (or especially) veterans of start-ups that have failed.

Background of Author and Company

G24 Innovations is a start-up company dedicated to the commercialization of the dye-sensitized cell (DSC). The history of how G24I learned to manufacture DSC cells, of the choices they made and the alliances they formed is a microcosm of the universe of new companies doing the same the world over with newly discovered technologies.

G24I began in 2006 as the vision of two entrepreneurs, Ed Stevenson and Robert Hertzberg. They are passionate about green alternative energy and the possibilities for DSC to make the world greener. Ed Stevenson had long followed the progress of DSC from its inception in the EPFL labs of Michael Graetzel in 1979. After selling his previous company, Ed brought together licenses from EPFL with licenses from Konarka Inc. that enabled the manufacture of roll-to-roll, web-based DSC photovoltaic material. He and his business partner Robert then built a plant in Cardiff and an automated production line.

The author, John Meschter, is a mechanical engineer with 33 years experience building high speed roll to roll automation and developing web-based products.[1] He has worked in large corporations and in four start-ups, three of which are in the field of alternative energy. He is responsible for developing new materials, processes and device architectures at G24I.

While this article speaks with an insider's knowledge of the business and the technology, the opinions expressed are solely those of the author.

Perspective of this Article

It is one thing to deductively distill the activities of many companies into a checklist of 'how it is done'; it is quite another to look inductively at one enterprise and understand 'why it was done that way'. The mistakes and the choices are instructive. If you give a man a fish, he can eat for a day, but if you teach him how to fish he can eat for a lifetime. Above all, looking anecdotally at a single company emphasizes the reality of the process: it consists of many, many iterative loops and switchbacks, and it is never the straight line of progress implied in business texts. However, the business texts do provide a kind of scaffolding on which to build a story. First, we need to straighten out the process and simplify it into a few digestible chunks (Fig. 1). This is a dangerous oversimplification! But it is indicative of the overall (messy) process (Fig. 2).

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Business has many conflicting priorities and one overriding difference from academic research: profit. While often the emphasis in a university research program is to find the highest performance, the best efficiency, the highest extinction coefficient, the emphasis in business is singular: the business must make a profit. Thus the choices made as to components and overall performance may in fact not create the best photovoltaic device; they should create the optimally profitable device. This may mean that a dye with high stability will be chosen over a dye with high efficiency, or that a substrate with lower light transmission will be chosen due to lower cost.

The transition from academia to industry is like jumping out of an airplane flying north onto a train speeding west. The plane can fly anywhere and can see the geography from above; the train is on a prescribed and scheduled path that follows the contours of the land.

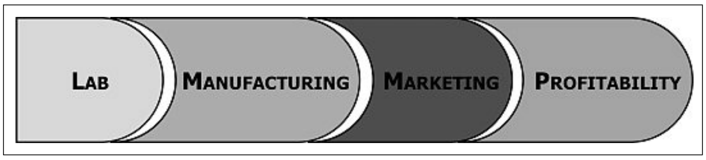

Fig. 1.

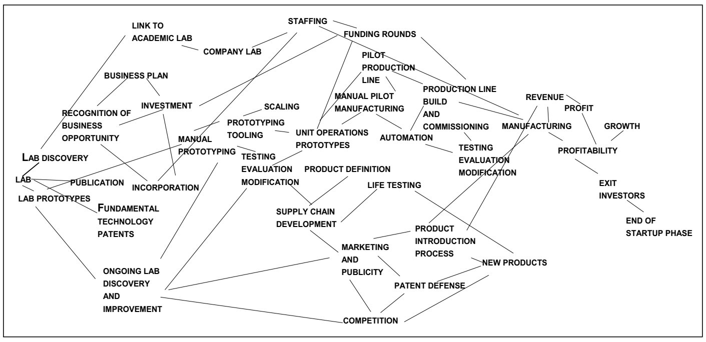

Fig. 2.

A Story about DSC

Dye-sensitized cells are made in the lab with two small pieces of glass, each about 2 cm square. Both pieces of glass have a sputtered transparent conductive oxide coating. Sputtering is a process done in high vacuum in which particles of a target source material are ejected by ion bombardment (*i.e.* sprayed, or sputtered) onto a receiving substrate. One of the conductive glass pieces has a 1 cm diameter spot, screen printed with a very thin and uniform coating of titanium dioxide (TiO_2) particles in a binder paste, and this coated glass has been subjected to very high heat (sintered) to burn away the binder and bond the TiO_2 particles to each other and to the conductive oxide surface. The other conductive glass piece has been coated with a thin layer of hexachloroplatinate and also sintered to precipitate platinum particles on the conductive oxide surface to act as a catalyst.

A small hole is drilled in the platinized piece of glass using an abrasive silica jet.

The just-sintered TiO_2 is immersed in a solution of dye and solvent for as long as 24 h, and then rinsed three times with acetonitrile and ethanol to remove any dye that has not adhered to the particulate surface of the TiO_2.

A thin sheet of a soft adhesive polymer called Surlyn is cut to the size of the glass pieces, with a 1 cm diameter hole to accommodate the spot of dyed TiO_2. The Surlyn is stacked on the dyed square of glass, then the platinized conductive glass is stacked on top of that, but offset from the bottom piece of glass so that the edges of the conductive oxides are exposed. Then the entire assembly is compressed in a clamp and subjected to heat to make the Surlyn melt and adhere to the glass pieces. In this way a small chamber is formed around the dyed TiO_2.

A droplet of electrolyte is applied over the small hole in the platinized glass, and the device is again put in a vacuum. The air inside the TiO_2 chamber is drawn out and replaced by the electrolyte.

The vacuum is removed and the outer surface of the glass is cleaned. A small glass disk is glued over the hole using another thin piece of Surlyn and another application of heat.

The exposed conductive oxide surfaces are ultrasonically soldered with a conductive metal to improve connection *via* clips to the testing machine.

The entire fabrication process exclusive of the time to dye the TiO_2 can take an hour or more.

The foregoing describes how cells are made in the lab: How then are these devices to be mass-produced at a low enough cost that they can be sold profitably?

The discussion that follows tries to answer this question by breaking it into a number of smaller but interrelated questions. The elegant device sitting on the lab bench has a long transformation to something that can be mass produced and sold. Of course, our bias is showing, as there are many products today that have no physical embodiment: software, algorithms for processes, business techniques, even books and films have nearly become weightless concepts in 'the cloud'. But we are talking about manufacturing and physical products; many of the concepts of physical manufacturing apply nonetheless to the growing list of 'disembodied' products.

About Manufacturing

There are a number of issues to be addressed:

1. How to make more than one at a time, and fast.
2. How to reduce the time each fabrication step will take.
3. How to simplify the number of steps.
4. How to measure and control variability to a level one order of magnitude better than required.
5. How to loosen the alignment required of all the elements to reduce the cost of aligning them.
6. How to make appropriate quantities of all the materials used – including yield loss.
7. How to reduce the cost of the materials used.
8. How to reduce the cost of the processes used.
9. How to automate the assembly of the devices, or at least systematize the assembly.

Aside from the technical issues to be addressed, there are always the other priorities of business:

1. How much time will it take to create a production system?
2. How much money will it cost to set up production?
3. How many people will it take to execute the project as efficiently as possible, and what are their skills sets?
4. What about licensing?

Indeed, there are other questions that we won't discuss here:

5. Where will the money required come from?
6. What are the products most likely to be accepted by the market and what distribution channels are needed to deliver the product to market?
7. Who are the materials suppliers who can furnish the component materials in quantity? What about new materials?
8. Is the market demand sufficient to justify manufacturing the product so that it is profitable?

These questions should not be taken individually. Rather they should be iteratively reviewed as a group because the challenge is not to optimize for any single aspect but, as with a non-linear programming optimization, to optimize for the best overall system. Thus the manufacturing system might be quite costly if it leads to a very low per-unit cost to manufacture. Or a material with a very high cost per unit area or volume might be used if it reduces the cost of other materials enough to justify it.

In addition, options as to manufacturing methods must be seen as a spectrum. At one end of the spectrum is the model shop: this is a workshop containing versatile tools such as milling machines and lathes and welders and plating equipment, sputtering machines, shears and measuring tools. It has highly skilled, highly paid workers who have experience making many different kinds of parts and assemblies. A shop such as this can make just about anything, but usually in small quantities, by hand, one or two at a time.

At the other end of the spectrum is a high volume assembly line. One example of this is the so-called roll-to-roll assembly line. The advantage of roll-to-roll is the continuous nature of a moving web of rolled material on which different components are placed and to which different operations are performed. This end of the spectrum is very inflexible, usually dedicated to making one configuration of matter in very high volume. It is usually run by operators with less specialized and less versatile skill-sets, and consequently lower pay rates.

This manufacturing spectrum must be matched to the perceived or known needs of the market. If the variety of products demanded by the market is large and the volumes for any one version of the product are medium or low, a manufacturing system with more of the model-shop functionality, such as batch production or manual unit operations is appropriate.

If the variety is low and volume is high, then a high volume automated roll to roll production system is indicated. In some instances, hybrid systems make the most sense. Such a system might produce, as a precursor, a 'plain vanilla' form of the product with high volume methods, and then this production is split into many, low volume, low automation streams in order to customize the product to specific versions. An example of this is cake making, where large vats of batter are baked into pre-formed cakes and then specialized with decorative icings into birthday or wedding or party products.

Step by Step

Let's go through the lists above one at a time and then look at the problem as a whole.

1. How to make more than one at a time – preferably in a continuous fashion instead of in large batches.

A car engine running at a constant speed with stable temperature and good lubrication will run for the equivalent of many hundreds of thousands of kilometers: it is the starting, stopping, accelerating and warm-up that cause most of the wear on the engine. In a similar way, processes that reach a stable operating plateau can continue for long periods with little variation. In short, the transients are avoided.

This is especially true in coating operations. At Polaroid, the once-mighty instant picture company, the coatings of the negative web were done on 2 m wide, 1000 m long rolls, because the transient variations in flow rate of the multiple coating heads could take 10's or even 100's of meters to settle. When the web had to be spliced to a new roll (again to 'keep the line running') specially trained operators made the joint between the two webs (the 'splice') while the web was moving, because this avoided large disruptions to the coating process. The master rolls were individually worth almost 1 million dollars each – no one wanted to ruin these!

Continuous processes are inherently high volume. This means that the labor and capital equipment cost is amortized over many meters of material, and the cost per unit of product is reduced. Thus if any aspect of our DSC manufacturing can be continuous, we can create the competitive advantage of lower cost.

Continuous processes are generally expensive, too. This is because all elements of the machine must be able to respond and correct for error or misalignment in real-time, and control to high precision.

There is nothing wrong with batch processes – most foods and pharmaceuticals are processed in batches to insure that variations in a batch are caught and corrected immediately. This is perhaps the downside of continuous production: if there is an offset in a process parameter, an awful lot of material can be processed before that error is corrected. This highlights the importance of good process controls.

In the instance of the DSC, we must think about the elements of construction and decide if some or all of these can be done in a continuous process. One aspect that stands out: there is a thin and very uniform coating of TiO_2 applied to one glass substrate. Might this be a candidate for the benefits of stable continuous coating? It is done in the lab with screen printing (the way T-shirts are printed). Is screen printing a process that can be done continuously? Or is there a better coating process that is less costly?

The testing and prototypes needed to answer the questions around 'what is the best way to make this' constitute the most important and underestimated phase of the transition from lab to production. The importance of having people with very different skill sets than are found in the lab can't be understated: knowledge and experience in manufacturing processes will shorten the time it takes by an order of magnitude, and will increase the chance that the process is industrialized and robust.

Moreover, this exploratory phase is where many of the iterations about product architecture and optimal configuration of matter will take place.

The production prototyping for G24I first took place at the laboratories of Lowell University in Massachusetts and later in the shops of Konarka Inc., near Lowell. The resulting pilot production line and the rights to use patented processes and materials (so-called Intellectual Property, or IP) were purchased at the founding of G24I, along with key personnel. Then, at G24I, the first full scale machines were built. The pilot work at Lowell and Konarka took place over the course of two years, and the full scale machines at G24I were built in about a year.

In retrospect, even the development work at G24I was too compressed; estimates of sales volume were too optimistic and the machine capacity was too large. It was too costly to run at first because demand volumes were low.

Small, low capacity lines are not efficient for high volume production, but the capital investment is lower and the cost of *replicating* a line is much less than designing and building one from scratch, since all the engineering and testing is already complete. Thus a good approach is to build a machine that can economically manufacture reasonable volume for a new product just introduced. If the product is a success, more capacity can be built quickly by *replication*.

Expect production know-how to be an ongoing, continuous process of improvement. The surprising thing today, six years after the founding of G24I, is that we are still learning, still improving, still finding new architectures and materials that improve our product and reduce its cost.

2. How to reduce the time each fabrication step will take.

One way to reduce time per step is to run continuously; the next logical step is to run continuously at high speed. This is not a panacea, as some steps of construction simply don't lend themselves to continuous motion, or cannot be justified in cost per unit at the intended annual quantities.

Another way to reduce the time per step is to eliminate the step! This is often the best and most overlooked approach. Is it possible to eliminate steps by using a different material? Can the functionality of the material be expanded to include, say for example, adhesion, or UV blocking, or scratch protection? Is the increased cost of the material less than the incremental cost of the manufacturing step it eliminates? This is often considered in chemical synthesis, where the purity or choice of the constituent precursor materials might eliminate a costly purification step later on.

For DSC, fabrication occurs in two categories: chemical synthesis[2] and blending, and mechanical assembly. In the instance of mechanical assembly, it is often a good idea to buy substrates pre-coated with adhesive, and if possible pre-stacked with different functional layers. Each layer that is laminated by the vendor (who is usually set up for this and can do it more economically) is one less run through roll-to-roll equipment. This has collateral benefits in that the fewer runs a roll has to make through processing equipment, the less wear and tear it sees, and the less chance for something to go wrong. Moreover, since every machine set up 'wastes' a little length of the roll at the beginning and end of the roll (for splicing, threading into the machine, taping to take-up rolls, *etc.*), the yield (ratio of finished product to equivalent raw materials input to the process) of the process is improved.

We can also eliminate steps by eliminating materials. Thus if the primary conductor electrode is robust enough to act also as the back side of the assembly, and doesn't need to be covered by a protective plastic laminate, we can eliminate the laminate and save on process, yield, material cost, product weight, product thickness and time to manufacture. Chemical synthesis is not performed at G24I but rather by working with collaborators. The role G24I plays in this effort is to test and evaluate increasingly large quantities of new chemistries, with shared results and feedback to the chemical manufacturer. The production and testing expertise of G24I accelerates the scaling of new dyes and electrolytes. And, similar to the reduction in time-per-step in mechanical production, chemical synthesis can be simplified by eliminating steps or using faster processes.

3. How to simplify the number of steps.

Think about making breakfast in the kitchen. Is the kitchen laid out well? Is the refrigerator near to hand, along with a sink and a work surface? How many steps are needed to go between them? Is the pantry out in the garage or just to the left of the refrigerator? Have you thought through what you will be making, so that while you are at the refrigerator, you gather and lay out on the work surface all you will need so as to avoid having to go back to the refrigerator? Does the workspace allow for 'short term' supplies to be amassed at hand for the assembly? Do you have proper pans and utensils to do the preparation tasks? Are they conveniently arrayed around you for quick access? Are environmentally appropriate waste receptacles also conveniently located? When assembly is complete, will the tools be easily cleaned and readied for the next meal, or do they require much disassembly and reassembly after cleaning? The foregoing should give an idea as to how a product should be analyzed for the steps it will take to make it, in terms of time and effort and energy expenditure. A series of assembly steps should flow, and all of the supporting infrastructure should be arranged for the purpose. There is another aspect to this as well: the architecture of the product should be arranged to make the sequence of assembly as simple as possible. Thus it is better if all of the wires that need to be attached can be attached at the same time and station, instead of at multiple stages of assembly.

In the instance of DSC, we have put considerable effort into our TiO_2 sintering to be sure that all treatments of surfaces and TiO_2 morphology are achieved in one sintering step. The plant is laid out in order to minimize handling of rolls between machines, and the machines have been shortened to minimize the materials used to thread a new roll onto the machine. Materials usage is studied to reduce the amount used, and to reuse or recycle wherever possible. Waste streams (which can be quite costly to dispose of) are studied, and processes generating a lot of waste or costly waste are eliminated or avoided. The use of solvents is minimized because of the costs of handling VOC and waste.

4. How to measure and control variability to a level one order of magnitude better than required.

Let's say I am making a product that must be one meter long. If I have a measuring stick with a mark only at every meter, then I can tell that the product is too long or too short or just right, but I don't know by how much. If I don't know by how much, it will be hard to improve my process, much less communicate to anyone else what is wrong. If my measuring stick is marked in decimeters, then I can say it is too long by 1, or 2, or … decimeters. The rule of thumb is that whatever degree of precision is needed in your assembly dimensions, the tool for measuring that dimension should be able to measure to at least within one tenth of the dimension accurately. And equipment must be specified that is capable of being *measurably adjusted* to at least within one tenth of the desired dimension. Thus if my process must be run at 20 +/–1 °C, I should be able to measure the process temperature to within 0.1 °C. In general (only a guideline) process controls need an order of magnitude better precision in order to control effectively. One of the costliest mistakes we made in scaling the lab processes to commercial production was not paying attention to proper measurement and control of the many important dimensions required during assembly of the DSC webs. If a machine can be adjusted, the adjustment should be *measurable*. This sounds such a simple thing, but you would be surprised how many adjustments in machinery consist of a bolt in a slot, with no scale for measuring the position of the bolt. This is rather like a hotplate with analog knobs where all the temperatures marked around the knob have worn off.

5. How to loosen the alignment required of all the elements to reduce the cost of aligning them.

A handy rule of thumb when moving house and packing your belongings is that it takes ten minutes to fill a box 90% full, and another 20 minutes to fill it to 99% full. So the best way to move efficiently is to buy 10% more boxes and fill them only 90% full. Likewise, when I set the table for dinner, knives, forks and spoons go more or less on either side of the plates, which are more or less in front of the chairs. This takes only a minute or two. But when a state dinner is held at Windsor Castle for Queen Elizabeth, twenty workers with tape measures and templates spend a *day or two* aligning all of the silverware and plate ware within tenths of an inch of perfect. If the dimensions of the product – thickness, roughness, curvature, alignment, hole size, temperature, color, to name a few – are as loose as possible, it will take less time and effort to make the product. This must be balanced with quality and lifespan of the product… I won't be inviting Queen Elizabeth to my home for dinner any time soon.

For the DSC product we have commercialized, we have worked always toward simpler architecture, looser required tolerances, with the caveat that simpler and looser must also improve function and life. Tight tolerance can quickly become a nightmare in assembly. If we would like to assemble two webs that are striped, and we would like the stripes of the first web to align with the stripes of the second web, we must concern ourselves with the width of each stripe, the spacing of the stripes, the starting position of the stripes from the guided edge of its web, and the precision with which we align one web to the other (Fig. 3).

In the example in Fig. 3, where A is the case of perfectly matched webs and stripes, the change in stripe width is only 5%, and the change in spacing ('pitch') is only 2%. It is immediately clear that misalignment is much easier than alignment. (And we have not misaligned the *overall webs* to each other in the above example!) The situation becomes even murkier when we attempt to move the webs, say, to compensate for variations in width or pitch, or try to balance all three. Finally, this example demonstrates only alignment along one axis – how much more difficult in three, or with angular misalignment!

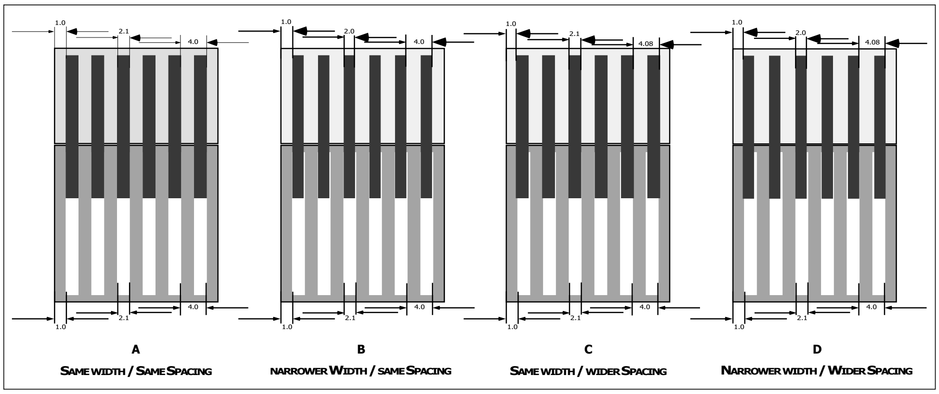

Fig. 3.

6. How to make appropriate quantities of all the materials used.

On the one hand, buying a cauldron to make a cup of soup is a waste of time, space and money. On the other hand, having to make soup one cup at a time for 20 guests is not only embarrassing but also not terribly practical. This is complicated by '*yield'*. Yield is how much good and saleable product comes out of a given process compared to how much *equivalent good* material went in. Thus in the soup example, some of the carrots and potatoes that were chopped up for the soup might fall on the floor or be otherwise spoiled. Or the cauldron might spill or the batch might be ruined because the fire went out. These are the random yield losses and are very difficult to control. Also there are the built-in variations in the process that cause yield loss: the part of the soup that always burns on the bottom of the cauldron; the part that spills when the cauldron is tipped into each bowl, the soup that is too salted or not salted enough because of an uncalibrated salt dispenser. Yield loss is cumulative – materials lost early in the process before they are combined with materials added late in the process cost less than nearly complete product that is lost in last steps. Machinery should be studied for yield loss – how much paint is lost when cleaning the tanks? How much web is lost in webbing up the machine? – and modified to minimize the losses. Then they should be sized to match all other aspects of the process throughput, *including* yield loss. The capacity of the equipment should be sized for the expected job, plus 10–20% for the unexpected. In general, we look at how long it will take to build and implement *additional* capacity. If it will take 6 months to add capacity, then we try to build capacity for what we expect during the next 12–18 months. This is modified by how much space and human resource is available, and how much disruption will be caused by adding capacity, and how much effort will be needed to match the quality of the existing capacity. In DSC, a major issue about capacity is complicated by the fact that DSC is a *new* technology and a *fast-evolving* technology. When we work with a supplier to develop synthesis methods for a new dye, a significant amount of time and effort is needed to arrive at a cost effective and pure substance. Suppliers are willing to build capacity for a synthesis stream if they can make enough of it and make it for a long enough period of time to pay for the capital investment and margin. If the systems of laboratories around the world who are working on DSC suddenly discover a better dye, both G24I and the supplier can be caught with an obsolescent plant and supply commitments that no longer make sense. The trick is to find a process that is sized to the best expected life expectancy. This risk is further minimized if the synthetic processes used are themselves common, industrialized, commodity processes, so that if the particular dye synthesis becomes obsolete, the equipment has a better chance of finding a new use in another process. Because of the impact academic research can have on the economics of a DSC synthesis process, we as a company lean toward those dyes that are simple to fabricate and purify with standard industrial synthesis steps. An awareness of this at the lab level could influence the kinds of chemistries chosen for development.

7. How to reduce the cost of the materials used.

The world is a very large place. It is likely that someone, somewhere, is making the material you need at a lower cost than where you now source it. The question to answer is if that lower cost material is of sufficient quality to replace the material you are using, and if the costs of delivery don't outweigh the lower material cost. It is also quite likely that there are other less costly materials that can do the same job or better than the material you are using now. And of course, the material with zero cost is the material you can avoid using at all. The subject of materials and how to minimize their cost is an ongoing, never-finished process. It should be carefully considered in the scaling-to-commercial-production program using the best information available at the time – from the very beginning! – and understanding that materials and methods will always improve and change. In DSC, we are constantly testing new barrier materials, new adhesives and substrates, alternative suppliers and competitive bids for existing supply contracts. This is part of the technology roadmap. In addition, the lab is always evolving better chemistry, and this too is subject to constant evaluation. The interaction between G24I and Dr. Graetzel's labs at EPFL is centrally important in the testing and development of new materials. The labs provide our first 'gate' in understanding the fundamental chemical compatibility or interaction between new materials or chemistries. Often the analytical capabilities of the labs have been specialized for DSC and can provide deeper and faster insight into, say, catalytic reactions or corrosion of conductors. Moreover, many materials are suggested by the ongoing research work, so the process of evaluating materials for cost and performance is a two way street. G24I has production capacity to perform large scale testing of new chemistries, which becomes the ultimate testing ground for the dyes and electrolytes developed at EPFL.

8. How to reduce the cost of the processes used.

Most of the costs of a product are 'locked-in' by the choices made at the conception of the product. This can lead to fantastic products that no one can afford to buy. Thus the surface treatment that can only be made with batch processed ALD (Atomic Layer Deposition) conformal layers, or the chemicals that can only be purified with expensive and slow Sephadex® columns, rather than the continuous bath passivation and rapid recrystallization purification of high volume, commodity industrial processes, can make a decisive difference in the ability of a product to compete against other products or even to be saleable. An example affecting many industries today is the lack of a transparent conductive material that is easily and rapidly manufactured in continuous processes. The widely used ITO (indium tin oxide) conductive coating can be deposited only with vacuum sputtering in a batch process, at high temperature. The enterprise that finds a viable alternative will have a ready market for its products! In all of our 'cost-down' projects, G24I searches for materials that can be made with widely available and well-characterized processes. A corollary to this is to try to use materials that are widely used as well. This usually means that significant plant and equipment is already extant in many competing companies selling into many markets. In this instance we can take advantage of the competitive pricing available for commodity products.

9. How to automate the assembly of the devices, or at least systematize the assembly.

If all of the foregoing issues have been addressed, certainly the job of automation is easier. What is automation? It is reducing or eliminating the use of, or need for, human interaction or intervention in the assembly of a device. In some cases, the *cost of labor* is so high that it is imperative to remove the labor content and then a high level of automation is justified. This is seen in developed countries with nice but costly medical plans and pensions and environmentally conscientious but costly manufacturing techniques. In other instances, the cost of labor is so low that almost no automation is economically justifiable, since it is easy to hire inexpensive human effort.

However this is not the only justification for automation, and increasingly this is the case. It is simply not possible for human beings to assemble the millions of transistors on integrated circuits, or to make repeatedly and at high speed a car door that perfectly fits the car body. Tighter dimensional tolerances and the ever-smaller scale of devices can only be achieved with the precision and speed of mechanized automation. There are still choices: the unit assembly operations of a production line can be automated while the handling and transport of the devices between machines can be accomplished manually, or every step of assembly can be automatically fed, aligned and installed. Thus automation is not a single concept, but a spectrum of possible levels. The decisions regarding automation can be among the riskiest and most important for a new enterprise, as the costs of capital equipment are generally very high and take a long time to develop and implement. This last point bears emphasizing, as it is one of the most common poor assumptions made in the transition from a successful lab demonstration to commercialization. ***The time to develop and implement robust, high yield, reliable, low variability automation can take as long* or longer *than the efforts made in the lab.***

Decisions about automation also play into other aspects of a fledgling (or even well established) business: how many versions of a product does the market demand? Let's say that the market wants two different colors of the same product. Does this imply building two separate assembly lines, one for each color? Does it instead mean cleaning out the white paint and replacing it with black paint on the same assembly line in order to change the color? How many of each color should be made? What if the tastes of the market change – should inventory be kept to a minimum? Are different colors desired in different countries? At G24I, there was a complete paradigm shift in our manufacturing automation strategy because of the activities of another company who one day knocked on our door. When G24I began, the electronics industry had not yet concerned itself with the now-common concept of energy harvesting. This is a growing field in which available ambient energy is collected and converted to useful voltage and current to power autonomous devices. The energy can be heat, light, vibration, sound, radio waves, tidal motion, wave action on beaches, cars driving over roads, wind, and water flow – thus including most forms of alternative energy. Ambient energy is available but usually goes to waste. G24I's DSC panels are uniquely suited to harvesting the energy available in low intensity light such as is found indoors. But in 2006, the only efficient way to deliver the harvested energy at the correct voltage was to make individual DSC cells and connect enough of them in series (like batteries in a flashlight) to add up to the correct voltage. The first product that G24I commercialized was a backpack phone charging panel. This panel had 11 lanes – each lane being a cell producing 0.5 volts – so that the voltage from the panel was 5.5 volts, just right for charging cell phones of that era. Other companies who made different products incorporating G24I's modules requested different voltages. Some wanted 12 volts; others wanted 3. This meant that our production line had to be able to make webs with a different number of lanes for every product of a different voltage, or that a web with a maximum number of lanes had to be cut down and formatted to the correct voltage. This was a huge dilemma as we contemplated building new manufacturing capacity. Luckily for G24I, it was at just that point that Texas Instruments introduced themselves and asked to meet with us. It turned out that Texas Instruments had long considered a foray into energy harvesting in the form of a chip that could work at extremely high efficiency, but extremely low input voltage and current, and convert the low input voltage to a *selectable* higher voltage. Texas Instruments came to G24I because they had tested our photovoltaic product against others on the market and found that the DSC technology – and G24I's version of it – has unique low light advantages over all other light-to-electricity conversion technologies. Because of this, Texas Instruments asked G24I to partner with them in developing their new chip, that could take exactly the voltages that one or two of our cells produced, and change that voltage to the level needed. All of a sudden, G24I could manufacture one-cell modules, and convert the voltage output to whatever was needed for a particular product. The knock-on effect of this tiny chip to our production line configuration was profound. And it led to new product architectures that have higher utilized area and much simpler construction.

Next we turn to different, but certainly related issues that impact the scaling of lab devices to saleable products. It is perhaps because the technology development in a start-up exists in the ecosystem of a new business that the change from lab to manufacturer is like jumping from an airplane onto a train moving at right angles to the plane – business must make a profit, and is not concerned with technology perfection but the profitability of technology.

Business Priorities

1. How much time will it take to create a production system?

This is one of the first questions to be asked when contemplating a start-up venture (adventure?). Planning the work is crucial, not so much that a plan must be robotically followed as much as it will make you think and think and think about what is needed.

When settlers crossing the Rocky Mountains for the first time and without a map came to what looked like a promising mountain pass over to the other side, they were quite literally making life or death decisions about whether or not to take it. This is because the time it took to drag everything over hill and dale to discover that the pass only led to a higher mountain could use up all the food and other resources. The Rocky Mountains are littered with the remains of those wagon trains that made the wrong choice. If those settlers had been able to consult a map, in effect they would be following a known path. Without a map, if those same settlers could have flown up high enough to have an overview of the mountains, then they could have planned a path to the other side even though it was unknown territory. Of course, there were still flash floods and mountain lions and hostile inhabitants and snow and many other unknowns:…..

"There are a) the things that you know that you know; b) the things that you know that you don't know; c) the things that you don't know that you don't know. The one to worry about is c)."

Bearing this truism in mind, it is worth getting good advice from someone who has already 'done' a start-up or two. That person's wisdom about a) and b) and heightened awareness of c) will be worth whatever it costs to find and consult him or her. Next, whatever estimate you make of the time it will take to create a production system, *double* it because of c). If the technology is really new and cutting edge, *triple* or *quadruple* it. Finally, make a plan. This is like visualizing that high altitude overview of the mountains ahead of you. It won't give you all the unknowns, but at least it will force you to make a list of what you do know, don't know, and don't know you don't know. G24 Innovations has made some very good capital equipment decisions and some poor ones. One of the most serious was to underestimate the difficulty in controlling multiple stacked dimensions, and the other was too much enthusiasm as to the size and rate of acceptance of the potential market, which led to overbuilt capacity. The best decisions have been made when we make a plan, review it regularly, modify it (prudently) when necessary, and *follow it*.

2. How much money will it cost to set up production?

This is a corollary to the first business priority, but an estimate of costs can't be made until a plan is made. (It is hopefully implicitly clear that plans need to be made for all aspects of a new business venture and not only the ones concerning production. These interrelated plans must be internally consistent and together constitute a business plan. This business plan is precisely what investors and venture capital firms will ask to see first.)

There are many business decisions to be made about production: Do we make it or buy it? What is the *value added* by our innovative idea? Can we buy the rest or do we have to invent a way to make some of it? Will this all take so long that the money is gone before we can run the manufacturing line and sell product for a profit? There are many more questions than this, but a good organizing principle at the beginning of a start-up is to invest as little as possible in capital equipment and process: if it is available on 'planet earth', buy it for now. If there is a company better suited to make something you need that is not available already, have that company make it. If there is a company that specializes in manual assembly (so-called contract manufacturing) – use them. In short, don't spend a dime you don't have to absolutely spend except for the very few things you really have to do yourself because they embody what is new and proprietary about your product. This might at first be more expensive than doing it all by yourself. But you don't really know yet if it will sell (you certainly believe it will, but that is not the point). Without certainty, you should not be spending all your money (and time) on something someone else is already doing profitably. The worst outcome of this approach is that your product will be a blockbuster success, and you will have to grow much faster than anticipated to meet demand. And if it doesn't sell, you won't owe so much money to all of your friends and family.

Now, how much will production cost? Capital equipment is expensive, especially if it is custom built. It will take 6 to 9 months to build once you have prototyped all of the operations and have a demonstrated proof that each operation will work – even if the prototype POP (proof of principle) is powered by hand, make sure it works! The prototyping phase will take 6–9 months also, so the whole custom manufacturing process is about 1 to 1.5 years. Thus the first cost will be for the employees that you will pay for a year or year and a half, whether they are working on the production machinery project or not. Your business plan (which is only a best informed guess) should have given you an idea of initial volume, and the costing exercise will give you a first glance at what the product will cost, not including the costs of purchased raw materials, or the costs of marketing and delivering the product. This volume should be delivered by your equipment on a one shift, five day week; this leaves room for unexpected order volume and lower than expected machine yields (don't forget yield!!!)

The second cost will be the machinery automation builder with whom you will partner to build the equipment. Sometimes equipment has to be built in house, and arguably the POP's could be made in your shop. But the knowledge gained by your partner machinery builder in participating in the POP will be worth more than the money saved doing it yourself. The machinery building companies build custom equipment for a living and they are good at it. Unless *you* are, go to the experts. Write a careful, thorough, detailed request for proposals, and shop it to at least three machinery houses. The quotes received in response will be very different and you will learn a lot about the process you are trying to build. Plus, you will have a very good idea of the second cost of building production equipment. The third part is to plan, and get quotes on, a facility to house the equipment. These days, your grandmother's garage is NOT a good idea. Environmental controls, safety and health issues, fire hazards and support infrastructure make the planning of facility as important as the planning of the production process. The quotes will be diverse, but will give you very good visibility into what is needed. The fourth part is to plan space for the storage and preparation of raw materials. This can be part of the facility plan, but workflow and staging space is critical to efficient production as well. Finally, plan the staffing (and the staff to support the staffing!) of the production system. Look at the costs and the impact on incremental product.

Combined, plus 20% for contingency, you have a pretty good idea of what production will cost you. Unfortunately, this idea is based only on best available information and it will change as more information is available. Thus you should plan to review it and revise it often.

3. How many people will it take to execute the project as efficiently as possible?

Next to capital investment, staff is among the highest ongoing costs of doing business. Just as with machinery, don't hire anyone to do work that can be contracted or purchased unless the workload justifies full time employment. The planning described in previous paragraphs begins to serve its fuller purpose in addressing staffing needs because the workload and work durations should be clear. You do want the expertise gained during a development effort to be captured, and often this is best captured by hiring the person with the expertise, but not always. Insisting on good documentation that will make sense to a person unfamiliar with the work reading it 3 months later is another way to capture expertise. It is all a balance against cost. Hiring temporary staff is also a great way to get to know and identify 'keepers'. Because hiring and training and retaining personnel (enough on this subject for another article at least) is so costly, hiring only those with the potential to be with the enterprise long-term is very important. On the other hand, don't underestimate the staff required either. Founders and technology officers of start-ups are often preoccupied with finding the next round of investment, and get caught in a time bind whilst trying to also manage daily core business issues like process and automation development. Supporting staff functions (HR, payroll, pension management) must be provided for hired staff, but fortunately much of this can be outsourced. Finally, a good, experienced, appropriately educated expert can leverage his or her knowledge and can implement the project efficiently with a small team of younger, less experienced and less costly employees. Often the bottleneck with experts is that they don't have time to execute all that they know; with a competent staff they can keep many parallel efforts going by delegating the tasks of implementation to others and using their expertise to guide it.

What then are the core skills sets needed to get from the lab to the market?

• *Business*. Preferably with past experience starting a company. Can plan the work and then execute the plan. Must be well connected to investors and other financial resources. Must be experienced with the many *transients* of starting a business. Must realize that the person it takes to start a business is often not the same person it takes to run a business long term.

• *Technology.* Must be the *best* expert on the technology being exploited, yet recognize that other expertise is needed to commercialize that technology. Must be well networked to such technical expertise.

• *Project management.* Must be able to plan, delegate, execute, measure, revise. Must be able to build effective teams.

• *Marketing.* Must be experienced with product development and introduction. Must be well connected to relevant markets' advertising, publicity, distribution and customers.

• *Operations.* Must be able to manage overall activity of the plant.

The foregoing reads like a textbook in an MBA course, so there is no need to dwell on it here. However, I do want to comment on the Technology expertise. This is because it is a relatively rare individual who has the best expertise in a new technology AND a good network to individuals with complementary expertise in things like automation, product development, process development and scaling, plant layout, production and workflow planning, chemistry synthesis scale-up and so forth. This is exactly the dilemma that G24I faced when it began.

4. What about licensing?

It is often the case (as with G24I) that the technology developed at a university is patented by the university and must be licensed from it. In fact, licensing IP has become a major source of revenue for many universities, and has changed the intellectual landscape for many academics suddenly thrust into the spotlight of business. This is especially true as the difference between large labs and many production processes becomes smaller. In fact, in the US Craig Ventner turned the usual sequence of events on its head when he deployed mass production techniques to the labs in order to decode the human genome. Is the PhD researcher now to become an entrepreneur? At what point will researchers begin to demand ownership or share rights in intellectual property (IP) traditionally held (and paid for) by the university? At what point will the gravitational pull of business counteract the attraction of a tenured professorship? Where will there be the most intellectual freedom to explore, given the relentless need to balance research with funding at a university, and the need to profit from research in business? These are old questions, but there are continually new answers. Today, new businesses based on academically developed technology naturally will seek the expertise of the discoverer/inventor, and will seek to exclude others from access to him or her. If the discoverer/inventor has right-to-exploit, new businesses will be even more motivated to engage his or her services. And even if the university is the holder of all rights, start-ups will seek collaborative agreements through the university to insure access to relevant new developments in their technology. How then is the relationship between the university, the researcher and the start-up best structured?

In terms of motivation, and without making it sound too venal, the university wants to participate in the potential profits enabled by university employees, in equal parts to cover their costs in supporting such research, to enable future research, and to promulgate the name and reputation of the university to attract more funding and better researchers.

Start-ups want exclusive access to the technology (and to further developments in the technology), usually for no money up front and as little as possible in royalties later.

Researchers want to see their work published and cited, their research permanently funded with no more scrabbling for grants and research contracts, and, increasingly, to benefit from the commercialization of their research. Clearly, universities will have to move toward protection of IP that is inclusive of and remunerative to the researchers who create it, and that gives structured access to start-ups seeking to commercialize the work. But there is more to it than this, especially if universities take the longer view that comprehends the potential world-changing impact of work done by its researchers. Because the IP protection afforded by the comprehensive and worldwide coverage of patents is an expensive proposition, universities must judiciously assess which 'horses' in its stable of IP will most likely 'win' in the race to commercialization. Having made that choice, *it is in the interests of the university to best leverage licensing to existing businesses and start-ups not only to maximize license fees and royalty revenue, but also to maximize the chances of the fledgling industry created by the IP to succeed and flourish.* This is an act of balancing exclusive rights to a few with the reduced risks of less restrictive rights to many. In short, license too many start-ups, and they will all starve before leaving the nest. License too few, and a few predators can eliminate all of the offspring. This is not unlike the biological strategies of different species, where some produce thousands of offspring because of the low likelihood of survival of most of them, and others produce a few offspring who are carefully nurtured, protected and raised up until they are ready to defend themselves. Universities have to find the best balance and then commit to their licensees as a group. And until that group has gestated and matured to a point where they can venture out into the real world of commercialization, the university can help to nurture them. Thus universities enter into a partnership with their licensees, and this is not a static contract or commitment. It is dynamic and must be nimble enough to react to environmental changes like the emergence of competing technologies, the collapse of investor community funding, new discoveries in the technology, and competing IP from other universities or businesses. One of the very useful interactions between universities and their incubating start-ups is the protective function regarding IP: the larger university – usually by virtue of its sheer size and resources – can quickly stop other entities who are infringing patents, thus protecting the start-ups who could not on their own mount a very effective defense. This of course requires that universities be willing to go to court to defend their interests. In later stages, start-ups having IP license to manufacture from a university have leverage with suppliers who see profit in supplying material protected by the IP because the supplier needs permission to manufacture. But a more subtle interaction is the dynamic support a university can give in terms of collaborative access to the researchers, lab space and analytical support, finance-in-kind in the form of deferred fees and costs or services. The university becomes, in effect, a womb. How should the licensees regard each other? They are, after all, siblings. This means that they too must balance 'winner takes all' with 'survival of the species'. I think there is room for both good sibling rivalry and the power of dynasty. On the one hand, each start-up will develop its own unique identity in the form of process and product IP, trade secrets, expertise, key contributors, business structure, customer base, supply chain and strategic investment. On the other hand, there are shared goals and activities best served by pooled resources and teamwork.

I have mentioned elsewhere the potential utility of an industry (fledgling, no doubt) trade group with pooled resources to create public awareness, pursue legislative changes, publicize achievements, articulate competitive advantages of the new technology versus others, maintain contact files, industry gatherings and symposia, produce summaries and overviews of the body of published patents and published research work, identify experts and serve as a first contact point for potential customers or investors. There is more, much more, that such a group effort can produce at lower cost and less effort than if done separately. G24 Innovations have licensed the IP covering the work of Dr Graetzel and others. The opinions I have expressed above have certainly been formed and informed by the relationship between G24 Innovations and EPFL. G24 Innovations could not have made the progress to commercialization that it has made without the profound and ongoing support of the University, and the collaboration with Dr Graetzel and the members of his lab. To all of them we owe a debt of gratitude and more.

Putting all of this together

First, go back and read the way DSC cells are assembled in the lab. G24 Innovations uses roll-to-roll assembly to make its flexible DSC product. In roll-to-roll manufacturing we work with suppliers of substrates in long roll form. These substrates include polyester and titanium foil. We buy adhesives in two forms: long rolls of thin ribbon and as coatings applied by our suppliers on the polyester substrates. We purchase other polyester substrates already coated with conductive oxides and catalysts made by other roll-to-roll converters. Having all of our materials in roll form makes handling easier, and insures that once the line is running, there are long, uninterrupted supplies of the materials we will assemble into working DSC products. The rolls can be mounted at the front ends of our production lines and can run for hours unattended. We source TiO_2 according to a proprietary recipe from our own facility in the US. This TiO_2 is applied, also using a proprietary process originally developed at Polaroid, onto specially prepared and cleaned rolls of titanium foil. The TiO_2 is then baked onto the foil at very high temperature, not unlike the continuous chain ovens used in bakeries to mass produce cookies. (You may have seen them also at restaurants where they are used to toast slices of bread.) At the end of the machine the TiO_2 and foil are rolled up again and transferred onto a long line that unrolls the foil and soaks it in dye. The length of the bath and the speed of the web determine how long the dyeing is done. The same machine passes the just dyed foil through sequential baths that rinse and then dry the dyed foil.

The foil is laminated to a backing polyester substrate, and the adhesive is applied along the length of the web. Then the foil/TiO_2/polyester web assembly is laminated to the polyester web having a conductive and catalyzed surface using the previously applied adhesive. In a proprietary process, the electrolyte is added between the foil and the conductive polyester, and the finished DSC web is rolled up, ready for conversion into final module format.

In formatting, the web is unrolled into cutting machines that cut the assembled web into short lengths and perhaps also into different widths. Then the ends exposed by the cutting are sealed shut with adhesive tapes and heat. Conductor strips and protective electronics are added to allow connection, and comprehensive testing of the finished module is performed. Modules are then encapsulated for environmental protection if needed, boxed and shipped.

Given the above process, *notice how different it is from the hand assembled cells of the lab*! Notice also that there is still room for improvement: do we really need that backing polyester substrate? Is the final testing the best place to find out that the modules are good or bad, after all the value has been added, or could we find a way to test performance at each stage of assembly and avoid costly yield loss? Can we use thinner materials? Would a different process give us finished modules directly, without the formatting processes?

The future for G24 Innovations includes incorporating higher efficiency chemistries that have been developed in Dr Graetzel's labs and other labs around the world. It includes changes to our modules to make single large cells instead of many small cells in series. It includes new architectures that enable whole new categories of products, and this requires new manufacturing processes to implement them.

Thus we are never finished, and the evolution from lab to production is ongoing.

The marvelous new discoveries now sitting in labs at universities around the world will become the products of…… well, not tomorrow exactly, but at least of next year or the year after. Recognizing that there is a significant amount of work needed to commercialize a technology is the first step, and then recognizing that there is a methodical approach to identifying and planning what work must be done is the second step. Hopefully, this article has given some insight into the issues and solutions of creating a manufacturable product and a production process to manufacture it. And further, these insights ought to help a little with making the decision to start a manufacturing venture.

Last is a personal comment: there is nothing that I know of in my professional career that has been more satisfying than seeing an idea transformed into 10's, 1000's or 1000'000's of products, moving off the production line every second in a highly choreographed and synchronized interaction of people, materials, and machinery.

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[1] 'Roll to roll' and 'web-based' are two terms describing a kind of automated production where long rolls of thin plastic or metal foils are progressively coated, stamped, slit, formed, welded, soaked or laminated to form stacked architectures of different materials in roll form. These can then be cut or punched into pieces, each of which has a product function. Examples are newspapers, diapers, gaskets, diabetic test strips, and, of course, DSC photovoltaics.

[2] A note about chemistry, academia, industry, and other start-ups: Chemical synthesis is not the charter of G24I. However, G24I is better suited than even university labs to test the utility and performance of new chemistries, because it can test the chemistry in production and on a large, statistically significant scale. Because of the ability to test not only chemistry but new materials, G24I has evolved quite a large analytical lab at the plant that does process control monitoring of production and analysis of new material and chemistry performance. In addition, G24I has substantial investment in life testing equipment as part of production and product improvement; these same facilities are perfect for rapid evaluation of the stability of new chemistries and materials in the DSC device. Once a new technology has begun to be commercialized, the commercial enterprises become part of the academic research efforts as well. Because G24I is making and consuming materials in much larger quantities than all of the labs combined worldwide, the consistent quality and uniformity of the materials G24I consumes are much in demand for continued lab research! This is true also of materials, substrates and even processes. The iterative feedback from industry to academe can serve to validate and accelerate academic research as much as the research can enhance the industrial enterprise, but only if the network of liaisons are established and maintained. This is why G24I set up an independent laboratory on the premises of EPFL, near to the labs of Dr. Graetzel, in order to open wide the doors to collaboration and communication. This collaboration has been central to the accelerated efforts at G24I to move to new redox chemistries, and has similarly fed back materials, processes and analytical information to the labs. In a new industry, it is not the other start-ups working on the same technology who pose the largest threat. Rather it is the survival of the new industry in the ecosystem of established industries that is of central importance. Thus, without necessarily sharing trade secrets and intellectual property, it is very useful and productive to meet regularly with other players in the field. There are many shared goals that can be efficiently served by working together – and at lower cost. Publicity about the technology is one example where pooled resources can have a greater impact. But also, databases of information concerning sources for materials, machinery builders, investor networks, libraries of research papers and published patents, testing results against international or national standards, comparisons with older, extant technologies and visibility into the 'who's who' of the nascent industry can help insure the survival of everyone.