

# Singapore NanoEnergy Report

Hiranmayee Vedam

Weijie Kong



Information presented in this report apart from the information credited to other sources identified is considered public information and may be distributed or copied. Use of appropriate credit is requested. We welcome suggestions on how to improve this report. NanoConsulting Pte. Ltd. provides no warranty, expressed or implied, as to the accuracy, reliability or completeness of furnished data.

For further information  
Contact:  
**NanoConsulting Pte. Ltd.**  
20 Maxwell Road #09-17  
Maxwell House  
Singapore 069113  
Email: [sgecosystem@nanoconsulting.com.sg](mailto:sgecosystem@nanoconsulting.com.sg)

© NanoConsulting Pte. Ltd., 2010

## Table of Contents

|   |    |
|---|----|
| 1. The Singapore Energy Policy .....            | 2  |
| 2. Nanotechnology in Energy .....               | 3  |
| 2.1 Energy Generation.....                      | 3  |
| Photovoltaic Cells .....                        | 3  |
| Fuel Cells .....                                | 4  |
| Wind Energy .....                               | 5  |
| Fossil fuel.....                                | 5  |
| Others .....                                    | 5  |
| 2.2 Energy Storage .....                        | 6  |
| Li-Ion Batteries .....                          | 6  |
| Supercapacitors .....                           | 6  |
| Hydrogen Storage .....                          | 6  |
| 2.3 Energy Distribution .....                   | 6  |
| 2.4 Energy Utilization .....                    | 7  |
| Transportation .....                            | 7  |
| Building.....                                   | 7  |
| Manufacturing.....                              | 7  |
| 3. Nanotechnology in Singapore.....             | 8  |
| 3.1 Photovoltaic Cells .....                    | 8  |
| First Generation PV Cells .....                 | 9  |
| Next Generation PV Cells.....                   | 10 |
| 3.2 Fuel cells .....                            | 11 |
| 3.3 Li-Ion Battery .....                        | 12 |
| 3.4 Organic Light Emitting Diodes (OLEDs) ..... | 12 |
| 3.5 Other areas.....                            | 13 |
| 4. Conclusions.....                             | 13 |
| 5. Acknowledgements.....                        | 13 |
| 6. References.....                              | 13 |

It is estimated that we would need to generate 60 terawatts of energy – equivalent of 900 million barrels of oil per day - around the planet if all the world’s population were to achieve the level of energy prosperity the developed world uses today [1]. Current estimated of oil reserves in the world are around 1000 billion barrels [2] which is sufficient to meet this kind of energy needs for little less than 3 years.

There are principally two ways to address this challenge. The first alternative is to increase energy efficiency thereby reduce energy consumption rate. It is estimated [3] that by increasing the energy efficiency of existing systems, we can reduce the equivalent of 64 million barrels of oil per day. The second alternative is to identify new energy sources and build the infrastructure compatible with these sources. As seen from Figure 1, currently, world’s energy is primarily derived from petroleum, coal and natural gas. As mentioned above, available oil reserves are insufficient to meet the future energy needs. Hydroelectric power has already reached its maximum energy potential. While coal is available in large quantities, the CO2 emissions associated with this energy source make

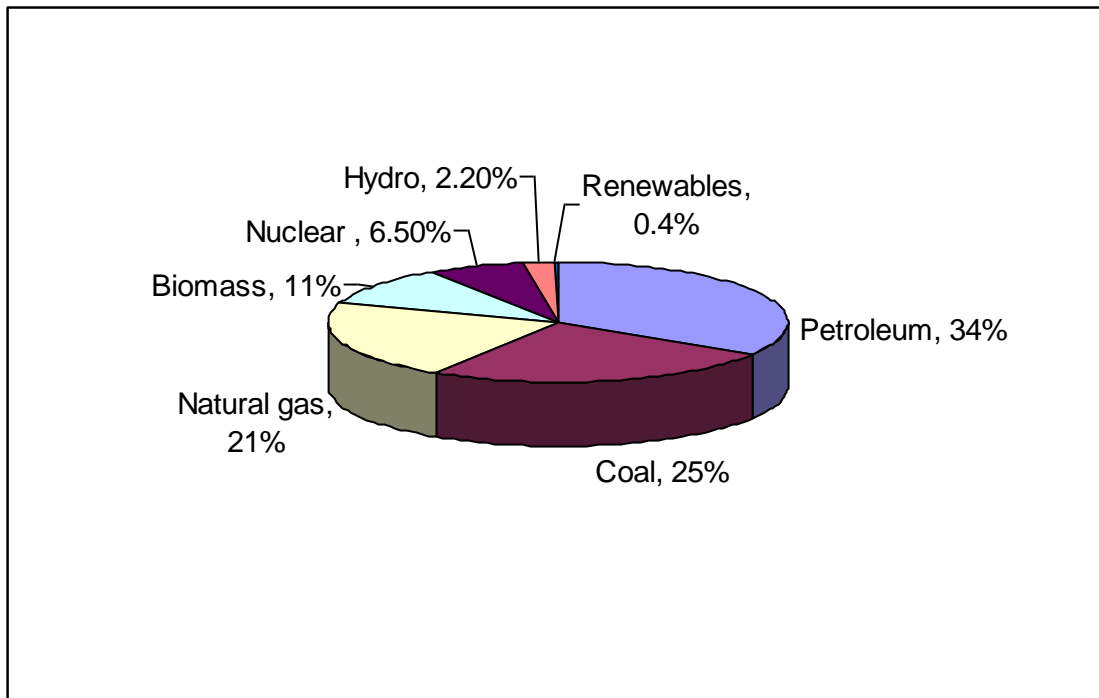


Figure 1: World Energy Sources, EIA World Energy Sources, 2006

it unattractive. Biomass energy sources also conflict with food sources.

In the short term the best way to meet the energy challenge is to increase the efficiency of existing energy sources and their utilization. Long term solution to the energy problem is to tap into nuclear, geothermal and solar energy sources with solar being the largest untapped energy source. Challenges to the nuclear solution are inadequate supply chains and lack of trained workforce. The nuclear solution is also fraught with concerns surrounding weapons proliferation, waste disposal and safety. Geothermal technology has

high capital costs and each project requires 5-7 years to complete. Solar photovoltaics are the most promising technology to address this challenge of fast deployment at reasonable price per watt.

## 1. The Singapore Energy Policy

In Singapore, the policies governing the energy industry which encompasses all organizations involved in generating, storing and distributing energy are set by the Energy Market Authority (EMA) - a statutory board under the Ministry of Trade and Industry. Policy input to EMA is provided by the Energy Studies Institute (ESI) which provides independent, quality and timely policy research and analysis of regional and global energy trends and issues in energy economics, energy security and the geopolitical and environmental impact of energy.

As in the rest of the world, this industry in Singapore is currently dominated by the oil & gas companies, which account for nearly 5% of its GDP. However in 2007 the Singapore government recognized energy as a strategic sector and embarked on new programs to broaden the base of this industry by exploring growth opportunities in solar power, fuel cells, biofuels and energy management solutions. The energy policy report [4] that was released in 2007 set a goal of increasing the value-added by the energy sector from S\$20 billion to around S\$34 billion by 2015 and to triple the employment generated from this sector from 5700 in 2007 to 15300. As part of its continued efforts towards building a sustainable Singapore, the National Climate Change Committee published a strategy [5] in March 2008, which outlines Singapore's current and future effort to address climate change in vulnerability and adaptation, as well as mitigation of greenhouse gases. Furthermore, Singapore has pledged to slash carbon emissions by 16 percent by 2020 versus current levels [6].

Singapore energy policy, which led to the energy sector being identified as one of strategic areas of development in 2008, outlines strategies to intensify energy R&D efforts in areas where Singapore has expertise or competitive advantage. As part of this strategy, the Singapore Initiative in New Energy Technologies (SINERGY) Centre [7] which will provides technical infrastructure such as a microgrid and command and control facility to facilitate research on clean and sustainable energy solutions was setup. The center also has in-house expertise in system integration, testing and evaluation of energy technologies. In addition, the Agency for Science, Technology and Research (A\*STAR) – an umbrella agency within the Ministry of Trade and Industry (MTI) which encompasses 11 different research institutes in Singapore - has established an Energy Technology R&D program [8] to integrate and expand existing knowledge and work in areas such as fuel cells, alternative fuels and next-generation solar technologies. A multi-disciplinary energy research institute encompassing six different energy centers to address different energy related-issues called Energy Research Institute @NTU (ERI@N) [9] was also setup in June 2009 at the Nanyang Technology University (NTU) to develop the energy related research capability in Singapore. The Singapore government also plans to setup the Jalan Bahar Cleantech Park [10] to be located next to NTU to provide a plug-and-play environment to test-bed cleantech solutions aimed at cities. In addition, the Sustainable Manufacturing Centre at SIMTech was created to work with the

manufacturing industry to develop and implement innovative technologies that reduce emissions, wastes and toxicity in manufacturing, promote the recycling and reuse of resources. One of their projects with a local biodiesel producer has validated a net significant reduction in carbon emissions due to carbon recycling [11].

Apart from research programs and infrastructure, Singapore is also raising awareness about renewable energy and Singapore's role in the developing this field through hosted global events such as the Singapore International Energy Week (SIEW) [12] which is an annual energy conference for industrial, political, and academia stakeholders to come together and share their insights.

To encourage the growth of the energy industry and innovation in this sector, the Energy Market Authority (EMA) announced a S\$25 million Energy Research Development Fund (ERDF) and S\$10 million Energy Market Development Fund (MDF) to give impetus to research development and demonstration initiatives that can help grow the energy industry, and provide incentives for developers to sell renewable energy into the grid. The Singapore Economic Development Board (EDB)'s Clean Energy Program Office (CEPO) set up a Cleantech Start-up Fund to help accelerate the commercialization of energy, water and environmental related technologies by providing a grant of up to 85% of qualifying costs for approved projects, capped at a maximum of S\$500,000 over a period of 2 years.

Due to these efforts, Singapore has a thriving alternative energy eco system comprising of the companies shown in Figure 2.

## **2. Nanotechnology in Energy**

Nanotechnology is the technology of creating and applying materials and structures with at least one critical dimension below 100 nm which lead to new functionalities and properties [13]. Nano-scale materials and structures exhibit many novel properties such as electric conductivity, magnetism, fluorescence, hardness and strength change which are significantly different from their macro-scale counterparts. Hence, nanotechnology offers infinite possibilities to develop innovative ways to efficiently capture, store, and transfer energy and hence address both the short term and long term energy challenges. Examples of nanotechnology applications in energy include zero loss transmission lines, super capacitors that could replace or enhance batteries (advanced lithium-ion batteries) and manage the energy grid more efficiently, more efficient solar cells, "green" highly efficient light bulbs, flexible electronics (laptops, TV's), cleaner coal fired power plants and more efficient fuel cells to enable the advancement of hydrogen powered cars.

### **2.1 Energy Generation**

#### **Photovoltaic Cells**

Photovoltaic (PV) cells that convert sunlight into electricity face two key challenges namely low efficiency and high cost of production. Inefficiency in conventional PV cells arises since the incoming photons must have energy equivalent to the band gap energy of silicon. This accounts for loss of 70% of radiant energy incident on the cell.

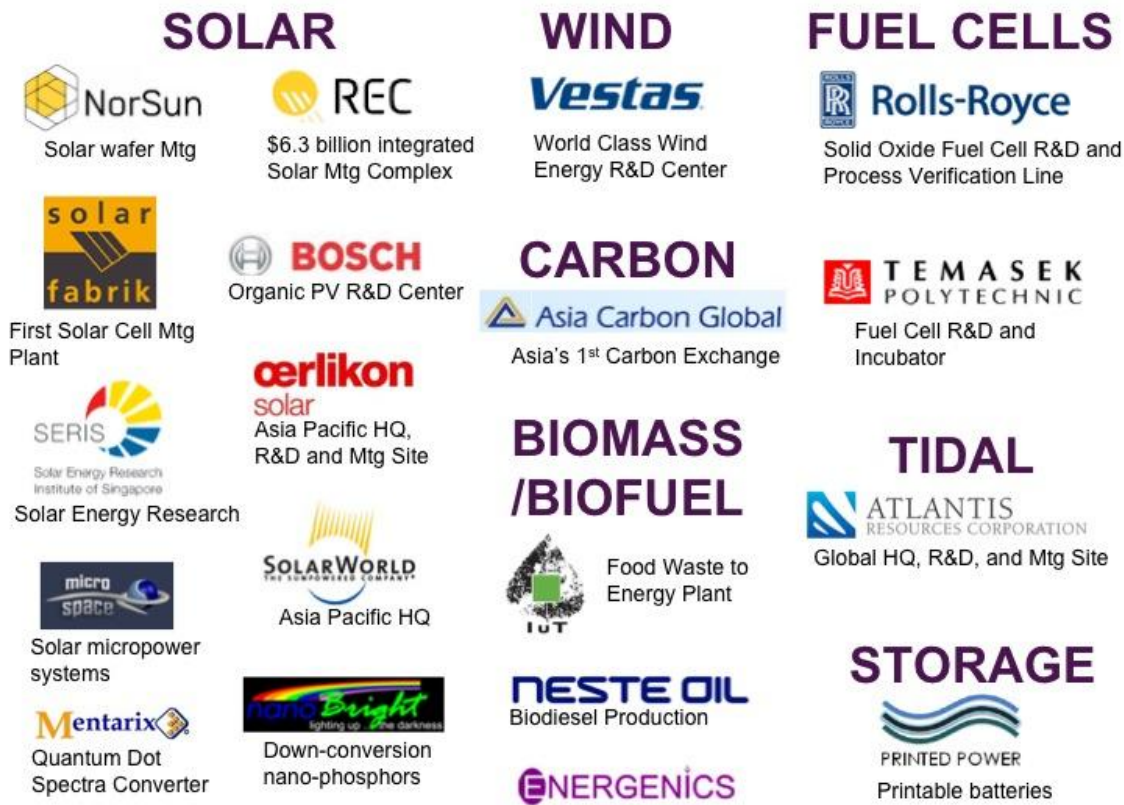


Figure 2: Alternative energy ecosystem in Singapore

Nanotechnology can help increase the efficiency of solar cells via multiple techniques. For examples, creating nanostructures such as quantum dots can help optimally adjust the semiconductor band gaps and improve conversion efficiency. Anti-reflective coatings using photonic crystals or non-metallic nano-layer systems can also improve efficiency. The use of plasma-aided procedures is another approach to optimize cell structures of all solar cell types and thus increasing efficiencies. Using nanotechnology it is also possible to manufacture inexpensive solar cells with the same efficiency as current technology. For examples, semiconductor nanorods or organic semiconductors can be embedded within a polymer matrix to create flexible and low-cost solar cells. Thin layer solar cells also have the potential to reduce costs due to material savings, low-temperature processes and integrated cell insulation. Dye sensitized solar cells made using titanium dioxide nanoparticles doped with dye molecules can be screen printed thus reduce manufacturing costs and can generate energy even from diffused light.

## Fuel Cells

A fuel cell is an electrochemical conversion device that produces electricity from fuel on the anode side and an oxidant on the cathode side, which react in the presence of an electrolyte. Key challenge in a fuel cell system is the high cost of producing and storing hydrogen. Apart from that the fuel cells use precious metal catalysts that are expensive and can be poisoned easily. The membranes used in the fuel cells cannot operate at

temperatures that are optimal for maximizing energy generation. It is also critical to measure the temperature profile inside a fuel cell in a robust and cost effective manner. Hence, apart from photovoltaic cells, nanotechnology has the most impact on this area of energy sector.

For example, nanoporous materials like complex hydrides such as  $\text{LiBH}_4$  and nanoporous metalorganic compounds are being developed to store hydrogen in solid state fuel tanks. Ceramic nanopowder-based on yttrium-stabilized zirconium are used to increase ion conductivity in SOFC. Nanotechnology enables the use of low-cost metal oxides to produce photoelectrodes that can increase the efficiency of water decomposition. Nanotechnology can also enhance the activity of electrode material and noble metal catalysts for electrochemical conversion of hydrogen. The temperature stability of membranes in the fuel cells can be enhanced through the application of inorganic-organic nanocomposites such as functionalized polymers with inorganic nanoparticles. Nanotechnology can also help overcome the key challenge of the need for hydrogen as a feed as nanocatalysts can be used to directly use hydrocarbons in the fuel cells. Microfuel cells with higher energy density than current batteries are also possible because of nanotechnology.

## **Wind Energy**

Wind energy provides less than 1% of worldwide energy needs but it is growing more rapidly than other energy sources. Key challenges faced by this energy are low efficiency & reliability of the turbines and difficulty generating high quality energy at low cost. Nanotechnology can improve the efficiency of turbines through nanocomposite materials based on carbon nanotubes that can be used to make lightweight and high strength rotor blades. Nanoscale coatings for bearings can also improve the efficiency of wind turbines.

## **Fossil fuel**

Fossil fuels currently provide for more than 80% of the energy needs in the world. As oil reserves become depleted, methods to extract more oil from existing reserves and new sources of oil such as shale are being explored. Nanotechnology is being increasingly utilized by this industry to increase production and efficiency. For example, nanosilicate particle suspensions are used for viscosity control in oil production. Nanoporous materials are also used for separation of contaminations in oil deposits and increase yield. Another area nanotechnology is used in fossil fuel production is the use of nanolubricants to reduce mechanical wear of drill probes used in exploration.

## **Others**

Nanotechnology also has a strong impact on energy generation using other sources such as geothermal and coal fires power plants. For example, nanostructured membranes can be used for separation of carbon dioxide in carbon neutral coal-fired power plants. Another example is the use of plasma coating processes can be used for thermal barrier layers in gas turbines. Nanoparticulate coating materials can also be used as ceramic anti-adhesive layers to reduce caking in heat exchangers in coal-fired power plants.

## **2.2 Energy Storage**

### **Li-Ion Batteries**

Li-Ion batteries that are ubiquitous in the market today have relatively high energy densities but high/low temperatures affect their capacity permanently. Also, shelf life of the battery irrespective of use deteriorates its capacity. None of the existing electrode materials and electrolytes can deliver optimal performance in high capacity, high operating voltage and long cycle life. Nanocomposite structures such as lithium titanate are being explored for anode material in these batteries. Similarly electrolytes containing nanoparticles are being developed to enhance the capacity of these batteries. These nanostructured materials also enhance the safety of Li-Ion batteries which can potentially explode at high temperatures or when exposed to stress.

### **Supercapacitors**

A supercapacitor consists of a two electrodes surrounded by an electrolyte separated by a membrane and stores energy by charge transfer at the boundary between electrode and electrolyte. The amount of energy stored is a direct function of available electrode surface. Hence, using nanostructured materials like carbon aerogels, activated carbon or carbon nanotubes can significantly enhance the performance of a supercapacitor.

### **Hydrogen Storage**

Efficient hydrogen storage is regarded as the key challenge in large-scale applications of hydrogen energy. Given that transportation consumes almost one quarter of the world total energy [14], on-board hydrogen storage receives the most intensive research efforts, aimed at realizing the commercialization of hydrogen-powered fuel-cell vehicles with hydrogen as a clean energy carrier. Material-based storage is expected to provide an ultimate solution to safe and efficient on-board hydrogen storage, because the well-developed pressurized tank and cryogenic liquid hydrogen techniques fail to satisfy the primary requirements of vehicular applications as a result of low volumetric hydrogen density, problematic energy efficiency, safety concerns, and/or high cost. Some efficient strategies, such as hybridization, cation/anion substitution and exchange, catalytic activation, and nanoscaling, morphology tailoring and surface modification are used to develop state-of-the-art materials for reversible or irreversible hydrogen storage. Nanoscaling has been demonstrated to be particularly effective for overcoming the kinetic barrier associated with diffusion (mass transport), and the enhanced nanoscale effect may also result in thermodynamic modification. Utilization of nanoscale confining techniques offers new possibilities to address the dilemma between dehydrogenation temperature and reversibility encountered in high-capacity hydrides [15].

## **2.3 Energy Distribution**

As energy costs continue to escalate, the power industry is looking for ways to reduce transmission costs while ensuring availability and flexibility. Nanocomposite materials like aluminum conductor composite reinforced wire or carbon nanotube composites have 5-10 times more capacity than the wires such as aluminum conductor steel reinforced wire that is currently used in the market. This will enable smaller foot print and lower construction/maintenance costs. Nanotechnology can also potentially help reduce the cost

of high temperature superconductor (HTS) wires, carry more power than current generation HTS cables and have lower maintenance costs. Fluids containing nanoparticles can cool HTS transformers more efficiently without the need for flammable liquids increasing flexibility in locating the transformers. Magnetoresistive nanosensors based on magnetic nanolayers and power electronic components are potentially self-calibrating and self-diagnosing enabling remote monitoring of infrastructure on a real-time basis. This would help decrease losses and increase availability and flexibility.

## **2.4 Energy Utilization**

Apart from enabling energy generation, storage and transmission, nanotechnology has a marked impact on increasing the efficiency of energy utilization in different industry sectors.

### **Transportation**

Nanotechnology impacts the energy utilization in transportation industry via nanocatalysts in fuels, nanolubricants to reduce friction, more efficient batteries and light weight nanocomposite materials that do not compromise on strength. Nanoparticles made of cerium oxide which catalyze the combustion between diesel fuel and air have been shown to increase fuel efficiency by up to 10% in field trials by Oxonica in 2006. Boric-acid based nanolubricants have the ability to reduce frictional losses by as much as 80% while increasing component durability and reliability. Nanostructured metal matrix composites and polymer composites can reduce the overall weight of vehicles. In addition, miniaturization of components through use of nanosensors can further reduce the overall weight of the vehicles.

### **Building**

The most significant contribution of nanotechnology to the building industry is by enabling the development and use of energy efficient LEDs based on inorganic and organic semiconducting materials. Quantum dots can help improve energy efficiency and light yield of existing LEDs by minimizing scattering effects. Nanotechnology can have significant impact on organic LEDs by optimizing the field carrier materials, succession and thickness of layers, application of dopants and the purity of the materials used. Nanocomposites made of polymers reinforced with carbon nanotubes can lead to ultra light high-stability construction materials. Heating and cooling of buildings account for a significant share of energy consumption worldwide. Nanoporous materials such as porous silicon dioxide based aerogels and nanoporous polymer foams that have smaller pore size than the average free path length of a gas molecule can help reduce these costs.

### **Manufacturing**

Nanotechnology can increase the energy efficiency of industrial processes through better insulation materials as discussed above. Nanostructured catalysts with larger surface area per unit volume can increase yield and give us an ability to synthesize materials in new energetically favorable ways. Nanoscale powders can reduce sintering temperatures in high temperature manufacturing processes like ceramics due to their large surface area and natural tendency to coalesce. Another way to increase energy efficiency of

manufacturing is to use microreactors where heat and mass can be controlled more optimally.

### **3. Nanotechnology in Singapore**

Nanotechnology is recognized as a key enabler to sustain future development of the Singapore economy, and Singapore agencies have put more and more emphasis on it since the late 1990s in response to the growing awareness of nanotechnology worldwide. The Singapore government spent about US\$300 million between 2003 and 2007 in nanotechnology-related R&D and manpower development. It is estimated that the number of researchers and engineers working in nanotechnology-related fields in the Republic, in both the public and private sectors, totals almost 1,000. Singapore is an active member of the Asia Nano Forum (ANF) as well as a participating member of the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) Technical committees on nanotechnology. Singapore also chairs the standardization working group in the ANF.

Singapore's research in nanotechnology mainly takes place in the two technological universities in Singapore namely, National University of Singapore (NUS) and Nanyang Technological University (NTU) and A\*STAR RIs. At NUS, the National University of Singapore Nanoscience and Nanotechnology Initiative (NUSNNI) provides the focal point for nanotechnology related activities. NanoCluster is an NTU-wide network of research centers with shared facilities for performing nanotechnology research. Among the 14 A\*STAR RIs, nanotechnology related research is concentrated in Institute of Materials Research & Engineering (IMRE), Institute of Microelectronics (IME), Singapore Institute of Manufacturing Technology (SIMTech) and Institute of Bioengineering & Nanotechnology (IBN).

To facilitate commercialization of nanotechnology research within NTU, the university with support from EDB setup NanoFrontier Pte. Ltd. - a nanotechnology incubator – to provide companies in various industries a platform to expand their research and development efforts in nanotechnology related areas. NanoFrontier also provides start-ups and technopreneurs a safe and strategic place to develop their nanotech inventions both technically and commercially. Singapore also has a number of private sector venture capital firms actively investing in nanotech companies. These companies are shown in Figure 3.

See [16] for detailed report on the Singapore nanotechnology ecosystem and visit <http://www.nanoconsulting.com.sg/whatWeDo/singnanonews.php> to get regular updates on it. The remainder of the paper will discuss some key developments in Singapore related to application of nanotechnology to energy.

#### **3.1 Photovoltaic Cells**

Photovoltaic cells are a strategic area of growth for Singapore. With its strong experience in the semiconductor industry, it has the engineering knowledge, infrastructure and experienced people required for the silicon based photovoltaics. It is also well positioned to integrate photovoltaics into the urban buildings. To capitalize on these advantages, in

August 2007, the Singapore Economic Development Board (EDB) launched the Clean Energy Research and Test-bedding (CERT) program, which will provide \$17 million in funding to test bed photovoltaic technologies. There are 31 grid-connected commercial solar PV installations with a total capacity of 422.1 kWp (as of June 2009) in Singapore. CERT and SCS will add another 4 MWp of installed solar capacity to Singapore's solar energy landscape [17]. The National Research Foundation (NRF) of Singapore has also set aside S\$170 million to boost Singapore's clean energy R&D efforts, starting with a focus on solar technologies and fuel cells. In February 2008, the National University of Singapore (NUS) set up a new national solar research institute SERIS to develop critical technological capabilities to drive the solar energy sector in Singapore. As part of its sustainable development program, Singapore has also earmarked \$31M dollars to install roof-top solar panels in 30 public housing precincts.



Figure 3: Singapore Investors in Nanotechnology Space

### First Generation PV Cells

Norway's Renewable Energy Corporation (REC) has setup the world's largest solar manufacturing complex in Singapore. Their first module has just rolled out in April 2010 [18]. NorSun has setup a major mono-crystalline wafer manufacturing facility in Singapore. Eco-Solar and Solar Power (acquired by SolarFabrik) have setup solar panel manufacturing in Singapore. Also, clean energy companies such as SolarWorld and Conergy have setup their Asia-Pacific headquarters in Singapore.

## **Next Generation PV Cells**

### **Dye Sensitized PV Cells**

Researchers at NUS are investigating the use of diameter controlled anatase TiO<sub>2</sub> nanofibers in dye sensitized solar cells. They are also researching the impact of electrospinning and hot pressing 1D metal oxide nanorods on to substrates as guides for electron transport. Initial results indicate that they can produce dye sensitized solar cells with conversion efficiencies of ~6%. Another group at NUS is investigating mesoscopic metal oxide electrodes (TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, etc.) and their assemblies with functional molecules to produce high efficiency, low cost dye sensitized and 3D solar cells. Other groups are investigating the use of conjugate polymers and nanocrystalline inorganic materials for solid state dye-sensitized solar cells. At Nanyang Technology University (NTU), researchers have developed dye sensitized solar cells based on ZnO nanoflowers with a conversion efficiency of 1.9%. BOSCH also opened a research and technology center in collaboration with NTU's ERI@N in the areas of DSSC and bulk hetero-junction solar cells. The Advanced Material Technology Center (AMTC) [19] at Singapore Polytechnic (SP) in collaborating with ST Engineering has set up the Solar Energy Test-Bed Application Center (SETAC) to enhance solar cell manufacturing capabilities and have achieved a large area cell efficiency of 7.8% by combining nanotechnology and flat panel display assembly techniques to manufacture dye sensitized solar cells.

### **Organic PV Cells**

A\*STAR's Institute of Material Research and Engineering (IMRE) has developed translucent organic solar cells that can be easily printed on flexible substrates. These solar cells can not only be produced cheaply but also can have wider variety of applications from window panes to portable electronics. At NTU, researchers are incorporating silver nanoprisms as median layer between the electron and hole to increase the amount of light absorbed and enhance charge transport. BOSCH has setup a \$30M R&D facility in Singapore and will collaborate with NTU to reduce the cost of their organic photovoltaics while raising their efficiency and service life. At NUS, platform technologies such as advanced nanometal inks, DUV and i-line crosslinkable formulations for producing organic transistors and novel columnar heterostructures for highly efficiency photovoltaics are being developed. Researchers at NUS are also investigating production of low-cost, high quality graphene by chemical exfoliation and its use in transistors and solar cells. Under the NRF's Competitive Research Program (CRP) Funding Scheme - which supports R&D programs comprising multiple related projects under a unifying theme for a maximum of S\$10 million per program over 3 to 5 years - many are in the field of photovoltaics. They comprise of research in nanomaterials like carbon nanotubes [20, 21, 22], graphene [23] [24] [25], and nanonets [26]. These next generation materials could be used for electronics and devices that could increase the efficiency of current renewable energy technologies. There is also research in innovative mathematical models [27] [28] for photovoltaic electronics.

Commercial activity in this area is just getting started in Singapore. Oerlikon has setup manufacturing and R&D facilities related to its thin film silicon solar panels. NanoBright Technologies Pte. Ltd. - a spin-off from NUS is increasing the efficiency of silicon based

solar cells using their up and down conversion materials. Mentarix – another startup from Singapore also uses quantum dots and photonic technologies to enhance the efficiency of all types of solar cells. Both NanoBright Technologies and Mentarix were awarded proof-of-concept grants under the Technology Enterprise Commercialization Scheme (TECS) [29] by SPRING Singapore which aims to catalyze the formation and growth of start-ups based on strong intellectual property with a scalable business model.

### **3.2 Fuel cells**

Singapore is one of the leading countries in fuel cell research [30]. The technology scan done by A\*STAR in 2005 as part of developing the Singapore Science & Technology Plan 2010 [31] included hydrogen production and storage and fuel cell based energy conversion technologies as two of the high priority research areas in energy sector for Singapore.

NTU has had an ongoing strategic program on fuel cells [32,33] for more than 10 years to develop next-generation fuel cells – more specifically high performance solid oxide fuel cells (SOFCs) that can operate at lower temperatures of around 600°C and membrane electrode assembly for low temperature proton exchange membrane fuel cells (PEMFCs). Key achievements of this work include the synthesis of ultra-dense high ionic conductivity YSZ-electrolyte of 0.17 S/cm, design of an anode supported fuel cell, development of PEMFC model that is validated experimentally, modeling of autothermal fuel reformer and hybrid gas turbine-SOFC for high efficiency power generation. NTU is also developing power electronics for power conversion and power conditioning in fuel cell systems. This work is continuing as part of the ERI@N in collaboration with Rolls-Royce, GasHub, Horizon Fuel Cell and P21.

Among the A\*STAR institutions, IMRE is developing new proton-exchange membrane electrolytes and small PEM fuel cell stacks. The Institute of High Performance Computing (IHPC) has research in computational modeling and analysis of PEM and solid oxide fuel cells, fuel cell materials and associated electrochemical and chemical processes. Singapore Institute of Manufacturing (SIMTech) is developing microfuel cells and new manufacturing technologies for fuel cells. The Institute of Chemical & Engineering Sciences (ICES) has research in fuel processing, fuel cell catalysts and hydrogen storage.

NUS is developing nanostructured catalysts and methanol-blocking proton-conducting polymer electrolyte membranes to overcome the challenges of catalyst deactivation and methanol crossover from fuel electrode to the air electrode in direct methanol fuel cells.

DaimlerChrysler along with BP and Michelin announced a fuel cell demonstration project along with installation of hydrogen refueling stations by BP. Rolls-Royce has set up an advanced technology centre to collaborate with A\*STAR institutions and Advanced Materials technologies to develop automated fuel cell manufacturing technology. Rolls-Royce also formed a partnership with a Singapore consortium led by Enertek Pte. Ltd. to form Rolls-Royce Fuel Cell Systems Pte. Ltd. to develop 1MW hybrid SOFC that meets electrical power system requirements. The Singapore economic

development board has setup a Singapore fuel cell community led by Temasek Polytechnic to support commercialization of fuel cell technologies.

### **3.3 Li-Ion Battery**

Research in Li-Ion batteries in Singapore although world renowned is a very niche area in Singapore. NUS has an advanced battery research group [34] which focuses on preparation and characterization of nanomaterials for li-ion and lithium polymer batteries. They formulating new transition metal oxide composites and modifying known oxide components ( $\text{LiNi}_{1-x}\text{Co}_x\text{O}_2$  and  $\text{LiNi}_x\text{Mn}_x\text{Co}_{1-2x}\text{O}_2$  doped with Al and Mg) as cathode materials. These new materials can potentially result in batteries that are robust to cycling and elevated temperatures. The group is also investigating composite alloys such as nanocrystalline  $\text{CaSnO}_3$ , carbon coated  $\text{CaMoO}_4$ , tin oxides with hollandite crystal structure, metal oxyfluorides  $\text{TiO}_2$  and  $\text{NbO}_2\text{F}$  and thin films made of  $\text{Fe}_2\text{O}_3$  and NiO nanoflakes and nanowalls as anodes. They have found that that nano-phase  $\text{ZnCo}_2\text{O}_4$  material is the best oxide material to use as anode material for Li-ion batteries. The group is also investigating polyethylene oxide (PEO)-Li-salt complexes as solid electrolytes in crystalline, glassy and polymeric form. Another group at NUS has developed Ru-doped cathode materials that have high charge rate and double the discharge capacity of commercially available cathode materials [35]. ERI@N has a large program on energy storage focused on new battery technologies for mobile electronics, electric vehicles and integrated energy storage using transition metal oxide based nanostructures, multifunctional electrodes and hybrid electrochemical capacitors. In terms of commercial activity in this area – Sony announced the opening of a new Li-ion battery plant in Singapore in August 2008 [36]. Printed Power – a spin-off from NTU focused on nanomaterial based printed primary and secondary batteries - received a TECS POC grant from SPRING.

### **3.4 Organic Light Emitting Diodes (OLEDs)**

OLEDs are light-emitting diodes (LED) that generate light in a film of organic compounds. A significant benefit of OLED displays over traditional liquid crystal displays (LCDs) is that OLEDs do not require a backlight to function.

IMRE and NUS researchers have developed a technology to fabricate all-in-one white LEDs by growing multiple quantum wells using InGaN/GaN on sapphire substrate. This is an important milestone in obtaining white light LEDs that are cheaper, stable and less complex without using phosphors. Another research group at IMRE is developing top emitting OLEDs on flexible substrates and has developed robust plastic substrates with effective barrier against oxygen and moisture to increase their life time. They have also achieved significant improvement in electroluminescent efficiency in top emitting OLED by overlaying an optical coupling layer on a semitransparent cathode.

Researchers at IMRE have also developed blue emitters with increased lifetime and efficiency that is solution-processible, making them cheap to produce. In the last year, there is an increasing emphasis on utilizing the learning from this research in photovoltaics development due to the strategic emphasis placed on the photovoltaics in Singapore.

Singapore also has a lot of commercial activity in this area. BASF setup an organic electronics R&D laboratory in Singapore and will include collaborative projects on organic photovoltaics with A\*STAR's IMRE. Ness Display setup organic LED manufacturing operation and conducts research in large scale display technologies in Singapore. Hyundai LCD Inc. has a collaboration with A\*STAR's SIMTech to develop and commercialize display manufacturing technologies for PM/AM OLED and flexible OLED for mobile and automotive applications. AMR International Corp has an ongoing collaboration with NTU to develop ITO transparent electrodes for OLED applications.

### **3.5 Other areas**

With skyrocketing oil prices, natural gas has huge potential to be the next primary energy source. However, there is a high content of carbon dioxide in natural gas, which if not separated, will not allow the gas to burn. Hydrogen sulphide also has to be separated from the gas or else it will corrode the pipelines. A team from NUS, with the funding of NRF CRP, aims to synthesize new materials [37] [38] with superior gas separation performance and to fabricate novel membranes with different configurations to meet market demand. Another group from NTU, also with the funding of NRF CRP, aims to learn from Nature on how to design artificial photosynthesis [39] systems capable of harvesting sunlight with high efficiency and stability.

## **4. Conclusions**

Nanotechnology has a profound influence on all aspects of energy generation, storage, distribution and utilization. Singapore has world-renowned research programs in the areas of fuel cells and Li-ion batteries and is fast becoming a hub for research activity in photovoltaics. This growth has attracted multinationals to do research and manufacturing in Singapore. Singapore has also accumulated more than 400 patents in the nanotech space. However, the local industry to capitalize on this technology and expertise is just beginning to emerge.

## **5. Acknowledgements**

The author acknowledges the support and comments received by her from Dr. Lerwen Liu, MD of NanoGlobe during the preparation of the first draft of this article.

## **6. References**

1. Richard Smalley, "Future global energy prosperity: The Terawatt Challenge", MRS Bullentin, Vol 30, June 2005, 412-417
2. <http://hypertextbook.com/facts/2000/EvanAbel.shtml>
3. Curbing global energy demand growth: The energy productivity opportunity, McKinsey Global Energy Institute, May 2007.
4. "Energy for Growth: National Energy Policy Report", Ministry of Trade and Industry Singapore, November 2007
5. National Climate Change Strategy, Mar 2008

6. Straits Times Online, 02 Dec 2010, "Pledge to cut emissions," [http://www.straitstimes.com/BreakingNews/Singapore/Story/STISStory\\_461605.html](http://www.straitstimes.com/BreakingNews/Singapore/Story/STISStory_461605.html) (accessed 23 Apr 2010)
7. SINERGY Centre - <http://energy.a-star.edu.sg/cos/o.x?c=/wbn/pagetree&func=view&rid=10123>
8. Energy Technology R&D Centre at A\*STAR - <http://energy.a-star.edu.sg/>
9. <http://www3.ntu.edu.sg/erian/>
10. EMA Statement of Opportunities 2009, pp. 33. [http://www.ema.gov.sg/media/files/publications/soo/ema\\_soo\\_2009.pdf](http://www.ema.gov.sg/media/files/publications/soo/ema_soo_2009.pdf)
11. "Singapore highlights new sustainable manufacturing center at SimTech," 04 Nov 2010, GovMonitor, [http://www.thegovmonitor.com/world\\_news/asia/singapore-highlights-new-sustainable-manufacturing-centre-at-simtech-13779.html](http://www.thegovmonitor.com/world_news/asia/singapore-highlights-new-sustainable-manufacturing-centre-at-simtech-13779.html) (accessed 05 May 2010)
12. <http://singapore.iew.com.sg/siew-2010>
13. Wolfgang Luther, "Application of nanotechnologies in the energy sector", Volume of the series Aktionslinie Hessen-Nanotech of the Hessian Ministry of Economy, Transport Urban and Regional Development, August 2008
14. D. Mori, K. Hirose, "Recent challenges of hydrogen storage technologies for fuel cell vehicles," Int. J. Hydrogen Energy, Vol. 34, pp. 4569-4574 (2009)
15. Chang Liu, Feng Li, Lai-Peng Ma, and Hui-Ming Cheng, "Advanced materials for energy storage," Adv. Mat. , Vol. 22, pp. E28-E62 (2010)
16. Hiranmayee Vedam et.al, "Singapore nanotechnology eco system", <http://www.nanoconsulting.com.sg/doc/SingNanoReport2009Feb.pdf> , Feb 2009
17. EMA Statement of Opportunities 2009, pp. 30. [http://www.ema.gov.sg/media/files/publications/soo/ema\\_soo\\_2009.pdf](http://www.ema.gov.sg/media/files/publications/soo/ema_soo_2009.pdf)
18. Syanne Olson, 23 Apr 2010, PV-tech.org, [http://www.pv-tech.org/news/a/recs\\_singapore\\_facility\\_rolls\\_out\\_first\\_commercial\\_product/](http://www.pv-tech.org/news/a/recs_singapore_facility_rolls_out_first_commercial_product/) (accessed 27 Apr 2010)
19. Singapore Polytechnic, Advanced Material Technology Center, <http://ctoo.sp.edu.sg/amtc/>
20. Chun Wei Lee, Cheng-Hui Weng, Wei Li, Yuan Chen, Mary B. Chan-Park, Chuen-hong Tsai, Keh-chyang Leou, C. H. Poa, M. Glerup, Junling Wang and Lain-Jong Li, "Towards High Performance and Solution Processed Field-Effect Transistors from Single-Walled Carbon Nanotube Networks," JPCC, 112(32):12089 (2008)
21. Kumar Raj, Xiaoyong Pan, Qing Zhang, Mary B. Chan-Park and Gao Pingqi, "Chemically induced air- stable unipolar-to-ambipolar conversion of carbon nanotube field effect transistors," Chem Phys Lett, 470: 1-3, 95-98, 2009
22. Jianwen Zhao, Xuanding Han, Chun Wei Lee, Yizhong Huang, Mary B. Chan-Park, Lain-Jong Li and Peng Chen, "High Yield Fabrication of Semiconducting Thin-Film Transistors Using Single-Walled Carbon Nanotubes Chemically Modified," Chem Comm, 46, 7182-7184, 2009
23. Manga KK, Zhou Y, Yan YL, Kian Ping LOH, "Multilayer Hybrid Films Consisting of Alternating Graphene and Titania Nanosheets with Ultrafast Electron Transfer and Photoconversion Properties," Adv. Func. Mat., Vol. 19, Iss. 22, pp. 3638-3643 (2009)

24. Ang PK, Chen W, Wee ATS, Kian Ping LOH\* et al., "Solution-Gated Epitaxial Graphene as pH Sensor," *J. ACS*, Vol. 130, Iss. 44, pp. 14392 (2008)
25. Wang Y, Chen XH, Zhong YL, Kian Ping LOH et al., "Large area, continuous, few-layered graphene as anodes in organic photovoltaic devices," *App. Phys. Lett.*, Vol. 95, Iss. 6, pp. 063302 (2009)
26. Cheng Sun, Nripan Mathews, Minrui Zheng, Chorng Haur Sow, Lydia Helena Wong, and Subodh G. Mhaisalkar, "Aligned Tin Oxide Nanonets for High-Performance Transistors," *J. Phys. Chem. C* 2010, Vol. 114, pp.1331–1336
27. W. X. Sheng, Y. Ding, F. H. Choo, P. Wang and P. C. Loh. (2009). The Eighth International Conference on Power Electronics and Drive Systems (PEDS09): Mathematical model of a solar module for energy yield simulation in photovoltaic systems., Taipei, Taiwan, R.O.C.
28. P. Wang, H. Zhu, W. Shen, F. Choo, P. Loh, and K. Tan. (2010). A Novel Approach of Maximizing Energy Harvesting in Photovoltaic Systems Based on Bisection Search Theorem. *25th Annual IEEE Applied Power Electronics Conference & Exposition (APEC)*.
29. SPRING Singapore, Technology Enterprise Commercialization Scheme, <http://www.spring.gov.sg/EnterpriseIndustry/TECS/Pages/technology-enterprise-commercialisation-scheme.aspx> (accessed 30 Apr 2010)
30. Mika Naumanen, Nanoroadmap project, VTT Technology studies, October 2004.
31. Singapore S&T Plan, - <http://app.mti.gov.sg/default.asp?id=885>
32. Hiang-Kwee Ho, Siew-Hwa Chan, San-Ping Jiang, "Fuel cell research, development and demonstration activities in Singapore" *Fuel Cells Bulletin*, June 2004.
33. <http://www3.ntu.edu.sg/mae/Research/Programmes/Fuelcell/intro.htm>
34. NUS Advanced battery group - <http://www.physics.nus.edu.sg/solidstateionics/>
35. "Enhancements of rate capability and cyclic performance of spinel LiNi<sub>0.5</sub>Mn<sub>1.5</sub>O<sub>4</sub> by trace Ru-doping", *Electrochemistry communications*, 11 (2009) 1539–1542
36. <http://www.mis-asia.com/news/articles/sony-opens-lithium-ion-battery-plant-in-singapore>
37. Y. Li, T. S. Chung, Exploratory development of dual-layer carbon-zeolite nanocomposite hollow fiber membranes with high performance for oxygen enrichment and natural gas separation, *Microporous and Mesoporous Materials*, 113, 315–324 (2008).
38. Y. C. Xiao, M. L. Chng, T. S. Chung, M. Toriida, S. Tamai, H. M. Chen, Y. C. J. Jean, Asymmetric structure induced by in-situ growth of silver nano-particles in carbon membranes with enhanced gas separation performance, *Carbon*. 48 (2), 408-416 (2010)
39. "MSE won its 3rd CRP \$10m Grant on Solar Harvesting," 28 Jan 2010, <http://www.mse.ntu.edu.sg/news/?op=news.html#3rdCRP> (accessed 30 Apr 2010)