Science & Technology Value Creation (STVC) 2015 Panel Report

Sustainable Development
Sustainable Development

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Executive Summary

In recent years, sustainability and sustainable development challenges have captured the world’s attention, and have galvanized international organizations, governments, corporations, non-government organizations and individuals into serious discussions and actions.

There is increasing recognition that the development of new green and clean technologies is not only important to protect our environment, but will also provide a clear opportunity and direction for the restoration and transformation of the world’s economies towards a more profitable and sustainable future.

Singapore, a densely populated urban centre without any natural resources, faces severe challenges in achieving sustainable development. Various strategies and initiatives are being actively pursued, including the use of a “Living Lab for Innovations” approach.

The Science and Engineering Research Council (SERC) is well-placed to contribute significantly to these efforts by establishing multi-disciplinary research programmes that support and serve Singapore’s sustainable development policies, strategies and needs (including its obligations in regional and international agreements), as well as enhance its economic and industry activities to export sustainable development products, services and solutions to regional and global markets.

A rigorous exercise based on the Siemens’ Picture of the Future (PoF) process was used to identify research programmes that could be recommended under the Sustainable Development theme. Relevant technological innovations were analysed based on their relevance to trends, user segments, functions, and living spaces. Potential programs were then identified based on the clustering of technologies in related areas. These programs were then prioritized, which yielded seven recommended programs – Waste Management, Sustainable Manufacturing, Sustainable Fuels, Chemicals and Materials, Solar PV, Green Buildings, Energy Storage, and Intelligent Eco-city Infrastructure & Systems.

For each recommended programme, key research areas have been identified and described, together with the economic and technological impacts and opportunities, and an assessment and stock take of R&D capabilities that can contribute to the implementation of each programme. For several programmes, research roadmaps and milestones have also been analysed.

The following paragraphs provide summaries of the key features of each of the recommended programmes.
Waste Management

The focus of this programme is on technological breakthroughs that would lead to higher value resource reclamation at lower cost, and an overall reduction in disposal. The main research areas are in:

- solid waste management (comprising waste sorting and separation technologies, waste collection systems, e-waste recycling techniques, waste to product, and waste to energy),
- liquid waste management (comprising water reclamation from wastewater, and chemical recovery and treatment), and
- integrated waste management systems (including the use of modelling and information technologies).

Sustainable Manufacturing

The scope of the programme focuses on the development of an integrated set of system-based enabling technologies that are critical to achieving sustainable manufacturing, with the following four areas of research being highlighted:

- life cycle engineering based tools and studies for critical sustainable manufacturing technologies,
- industry ecology map of Singapore to support the paradigm change towards sustainable manufacturing,
- Wastes-to-products/energy (W2PE) technology map for accelerating the implementation, as well as the research, of sustainable manufacturing technologies in Singapore, and
- strategic areas that are fundamental to a sustainable manufacturing industry: sustainable packaging and remanufacturing.

Sustainable Fuels, Chemicals and Materials

This programme’s research areas have been selected from the myriads of technologies under investigations around the world, and are categorised as follows:

- Development of alternative feedstocks (including conversion of coal to syngas, conversion of biomass to bio-oil, and energy crops)
- Chemical conversion of alternative feedstocks (including C1 processes, bio-oil to gasoline and biobased platform molecules)
- Biotransformation of alternative feedstocks (including lignocellulosic ethanol, fermentation of C1 substrates, and conversion of platform molecules)
- Carbon capture and utilization (including carbon capture and storage, and conversion of CO2 to fuels and chemicals)
- Biobased polymers and composites
Solar PV

This programme aims to complement the research activities of key local research centres such as the Solar Energy Research Institute of Singapore (SERIS), and will focus on emerging organic and nanostructured based PV technology. The programme will leverage on SERC’s strengths in materials synthesis, device development and integration, and materials analysis and characterization.

Green Buildings

The Green Buildings programme will pay particular attention to the development of technologies that cater to tropical climate, high-rise and high-density development and building form, highly glazed building façade and high dependency on cooling technologies, and will consists of the following:

• Sustainable Building and Construction Materials
• Cooling and Dehumidification Technologies
• Energy Efficiency, Self-Generation/Renewable Energies
• Building Automation/Management Systems

Energy Storage

The proposed research areas include:

• Materials and cell level research including new multi-purpose and nano-materials and advanced modelling of materials and fundamental processes and mechanisms
• Device level research including design and optimization, and thermal management
• Systems level research, including application-specific system optimisation and integration
• Manufacturing level research

Intelligent Eco-city Infrastructure & Systems

This programme will focus on technologies to create “intelligent” systems to serve eco-cities, and will comprise the following sub-programmes:

• Next generation smart grids to deliver reliable, efficient and cost-competitive power and energy services
• Urban transport systems, including intelligent transport and clean transport,
• Eco-city management, including integrated systems for city management and modelling, and technologies to enhance public security.
Chapter 1
Introduction of Sustainable Development Theme

1.1 Definition and Scope

Sustainable development has been defined as balancing the fulfillment of human needs with the protection of the natural environment so that these needs can be met not only in the present, but in the indefinite future\(^1\).

Sustainable development is an eclectic concept, and a wide array of issues and concerns fall under its umbrella. Several United Nations (UN) documents refer to economic development, social development, and environmental protection as “the interdependent and mutually reinforcing pillars” of sustainable development. The UN has identified areas that fall within their Sustainable Development scope\(^2\) to include Energy, Transport, Industry, Human Settlements, Rural Development, Biodiversity, Agriculture, Health, Climate Change, Fresh Water, Science, Poverty, Waste, and Sanitation, among others.

Figure 1 - Scheme of sustainable development: at the confluence of three constituent parts\(^3\)

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\(^1\) This is a widely used variation of the definition contained in the 1987 UN (Brundtland Commission) report (http://www.un.org/documents/ga/res/42/ares42-187.htm) that defined sustainable development as development that “meets the needs of the present without compromising the ability of future generations to meet their own needs”.

\(^2\) http://www.un.org/esa/dsd/susdevtopics/sdt_index.shtml

\(^3\) http://en.wikipedia.org/wiki/File:Sustainable_development.svg
The scope of the Sustainable Development theme under STVC2015 focuses on technological innovations and solutions which support sustainable development. They include, but are not limited to, technologies related to the following areas:

- **Sustainable energy and transport**, which encompass areas such as:
  - renewable and clean sources of power and energy, such as solar, wind, hydro-power, marine renewables, and bio-energy,
  - advanced and clean energy conversion technologies and fuels such as cogeneration systems, fuel cells, biofuels, and hydrogen,
  - energy and power storage and distribution technologies such as batteries, ultra-capacitors, and intelligent grids, and
  - energy efficiency technologies, including energy management systems, energy-efficient appliances, hybrid vehicles, heat pumps, and thermally activated cooling technologies.

- **Environmental protection**, which encompass areas such as:
  - clean manufacturing and technologies
  - climate change mitigation and adaptation technologies
  - local pollution control and mitigation systems; and
  - disaster management systems.

- **Resource conservation and innovation**, which includes areas such as:
  - waste management and recycling technologies;
  - new sustainable materials and alternative feedstocks
  - water production and treatment technologies; and
  - life cycle engineering and management.

Many of these clean technologies (“clean tech”) will be utilised in key application environments that are particularly important for sustainable development in urban environments, such as *smart homes, green buildings and eco-cities*.

### 1.2 Key Drivers and Trends

Research and development of technologies for sustainable development will be strongly influenced by the following key drivers and trends:

- Urbanization
- Depleting natural resources
- Environmental legislation, including carbon reduction and management policies
- Need for energy diversification and security
- Rising affluence, widening income gap, and population growth
Climate change and greenhouse gas emissions
Increased use of Info-Comm Technologies (ICT)
Increased sustainability awareness and thinking among individuals, corporations and governments
Increase in globalization
Short product and technological life cycle
Increase in general safety concerns
Increasing personalization and customization
Integrated personal devices

For example, it has been widely reported that urban centres account for approximately half the world's population, but contribute 75% of global energy consumption and 85% of greenhouse gases emissions. Technological challenges to enable sustainability with increased urbanization are therefore particularly acute and demanding - in areas such as transportation, environmental protection, waste and water management, public and high-rise housing, and public safety and security.

While many of these drivers and trends are of direct importance and relevance to Singapore as a city-state, it is also critically important to understand their broader influence and impacts on the rest of the world, as Singapore's economy is heavily dependent on the provision and export of goods and services to serve global markets.

Throughout the world, and even in competitive and free-market economies, there is increasingly wide acceptance that informed policy, regulatory and legislative decisions and actions by governments (both local and national) and international organizations (such as the United Nations) are critically important in determining the future direction and plans for sustainable development. Such decisions and actions are often needed to overcome market failures and excesses that are detrimental to longer-term goals and objectives in sustainable development. Of course, legislation alone will not be sufficient, but they provide the critical direction and support needed for other activities such as innovation and technology development to be pursued and conducted successfully, to meet the needs and challenges of sustainable development.

### 1.3 Key Global/ Local Developments

In recent years, sustainability and sustainable development issues have captured the attention of international organizations, governments of both developed and developing countries, corporations, non-government organizations, and individuals.
For example, a key challenge that has galvanized global interest and efforts is the threat of climate change and global warming resulting from increased greenhouse gas emissions, of which CO₂ from the burning of fossil fuels contributes the largest share.

What is perhaps most exciting for the research community is the increasing recognition that the development of new green and clean technologies are not only important to protect our environment, but also present a clear opportunity and direction for the restoration and transformation of the world’s economies towards a more profitable and sustainable future. For example, in his book “Hot, Flat, and Crowded: Why We Need a Green Revolution--And How It Can Renew America”, author Thomas Friedman writes –

“If you take only one thing away from this book, please take this: We are not going to regulate our way out of the problems of the Energy-Climate Era. We can only innovate our way out…”

Many world leaders have echoed similar sentiments. In a speech to the National Academy of Sciences on 27 April 2009, US President Obama announced the Advanced Research Projects Agency for Energy, and promised that

“…. We will make renewable energy the profitable kind of energy. We will put in place the resources so that scientists can focus on this critical area. And I am confident that we will find a wellspring of creativity just waiting to be tapped by researchers in this room and entrepreneurs across our country.”

At the United Nations, sustainable development is once again, taking centre stage. The United Nations Environment Programme (UNEP) and partners are launching a Green Economy initiative⁴ amidst what has been described as the most significant economic crisis since the Great Depression of the 1930s. This initiative, sponsored by the Norwegian Government, is to communicate a global plan for a green industrial revolution to be supported by strong and convincing evidence of income generated, decent jobs created, and poverty reduced through investing in a new generation of assets including:

- Ecosystems (or environmental infrastructure);
- Clean and efficient technology;
- Renewable energy;
- Biodiversity-based products and services (such as organic foods);
- Chemical and waste management and mitigation technologies;
- “Green Cities” - tomorrow’s habitat for humanity - with ecologically friendly buildings, construction, and transport systems.

⁴ http://www.unep.org/greeneconomy/index2.asp?id=gnd
Relative to the US (at least at the Federal government level), Europe and Japan have provided stronger leadership and consistency in sustainable development efforts, including in the area of climate change. The European Council has adopted an ambitious and comprehensive renewed Sustainable Development Strategy (SDS) in 2006, stating:

“The renewed EU SDS sets out a single, coherent strategy on how the EU will more effectively live up to its long-standing commitment to meet the challenges of sustainable development. It recognises the need to gradually change our current unsustainable consumption and production patterns and move towards a better integrated approach to policy-making. It reaffirms the need for global solidarity and recognises the importance of strengthening our work with partners outside the EU, including those rapidly developing countries which will have a significant impact on global sustainable development.”

This has also translated into an emphasis on Sustainable Development in Europe’s R&D efforts that are explicit and unambiguous. Thus, it has been clearly stated that the Seventh Framework Programme (FP7) “should contribute towards promoting growth, sustainable development and environmental protection, including by addressing the problem of climate change”. Moreover, it is explicitly recognised that the overarching aim of the “Cooperation” programme – by far the largest specific programme of FP7 – is to contribute to sustainable development.

All over the world, industry and the research community are also responding and rising to the challenge of developing technologies for sustainable development. The dizzying expansion in the solar and wind industry (albeit driven initially to a large extent by strong government initiatives and support, but moving rapidly towards “price parity” with conventional electricity generation), the interest in clean coal and carbon capture and sequestration technologies, the huge investments to develop next generation, environmentally friendly biofuels, the potential of reducing energy use in advanced water production and treatment, and the expected cost, efficiency, security and reliability benefits from “smart” (IT meets energy technology) grids and the electrification of the transportation system, are all reflective of this trend and interest in the “cleantech” industry.

Singapore, as a densely populated urban centre without any natural resources, faces severe challenges in achieving sustainable development. However, the Singapore government has, since independence in 1965, emphasized the

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6 http://ec.europa.eu/research/sd/index_en.cfm?pg=fp7-sustainability
creation of a “clean and green” environment while pursuing fast economic growth. As a continuation of its balanced approach, the government, through the Inter-Ministerial Committee for Sustainable Development (IMCSD), has recently unveiled its Sustainable Development Blueprint, a key document that contains strategies and initiatives the government believes are needed for Singapore to achieve both economic growth and a good living environment over the next two decades.

Over the last few years, (and in tandem with its decision to accede to the Kyoto Protocol in 2006) the Singapore government has begun to provide funding and support for a number of key R&D initiatives that are contributing significantly to the development of technological capabilities for sustainable development, and recently integrating these through a “Living Lab for Innovations” approach. Examples of these initiatives include:

- Strategic Research Programme on Environment & Water Technologies which include the Clean Water and Clean Energy programmes, funded by the National Research Foundation and hosted by the Public Utilities Board (PUB) and Economic Development Board (EDB), and includes the setting of the Solar Energy Research Institute of Singapore (SERIS)
- A*STAR’s Energy Technology R&D Programme
- Ministry of National Development (MND)/ Building and Construction Authority’s (BCA) Research Fund for the Built Environment, including the Zero Energy Building project
- Ministry of the Environment and Water Resources (MEWR)/ National Environment Agency’s (NEA) Innovation for Environmental Sustainability Fund

The fruits of these efforts are already appearing. For example, Singapore is now recognized as a “water hub”, with both MNCs and local companies providing global leadership in water technology development and application. Singapore has also attracted multi-billion investments for manufacturing, technical and business services, and R&D in various clean energy areas such as solar PV, wind energy, and biofuels. Beyond its own shores, Singapore is making an impact in contributing to sustainable urban development through high level initiatives such as the Tianjin eco-city project.

1.4 Bibliography


Chapter 2
Vision

2.1 Vision and overall goals

The vision of the Sustainable Development theme for STVC2015 is to establish internationally renowned, multi-disciplinary research programmes at A*STAR SERC and Singapore, that would support and serve Singapore’s sustainable development policies, strategies and needs (including its obligations in regional and international agreements), as well as enhance Singapore’s economic and industry activities to export sustainable development products, services and solutions to regional and global markets.

The overall goals of the programme are to:

- Build on existing capabilities in SERC, A*STAR, and the broader research community in Singapore to develop world-class research competencies and capabilities (including attracting and developing talent) and programmes in selected, and where appropriate, niche technological areas that A*STAR and Singapore can be competitive and effective, in relation to other organizations and countries working in the sustainable development research area. The recommended programmes for R&D under this theme are outlined in Section 2.4 and further discussed in Chapter 3.

- Transfer research outputs, innovations and breakthroughs to support and enable the commercialisation of novel, cost-competitive, market/mission-oriented, potentially disruptive/game-changing, and environmentally sustainable innovations, technologies and solutions through research and development activities and projects that are conducted in close collaboration with local and international industry and public sector partners.

- Contribute to the creation and development of competitive clean technology (“clean tech) and sustainable urban solutions industry clusters, that would establish Singapore as a living laboratory for sustainable development technologies and solutions, and become a hub and model for sustainable development practices and solutions. This could include participating in whole-of-government committees and task forces to drive specific sustainable development-related initiatives.

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7 Public sector partners include all public sector agencies and research organizations at the international and national levels
• Provide independent and sound technical support (if asked) to public sector organizations responsible for the formulation and implementation of policies, strategies, and regulations in sustainable development-related areas.

2.2 Needs and Challenges

In line with the wide range of topics and issues related to sustainable development, the needs and challenges for R&D within the sustainable development theme are broad and diverse. They will be discussed here using some of key functions that were identified as important for new technological innovations to provide (to end-users), if they are to become useful and competitive in the marketplace.

2.2.1 Analyse, monitor, assess, diagnose, predict and prognose

Research into techniques and tools incorporating holistic life cycle engineering and analysis are needed to properly assess the economic, energy and environmental factors associated with technological products, services and systems.

Technologies to help analyse, monitor, assess the state of the environment, and engineered systems that sustain human well-being and economic activity are also critically important as part of sustainable development.

This could include intelligent data/signal processing, sensors, measurement and data acquisition systems that will monitor and assess the state of the environment in real-time to ensure safety, security and environmental quality (for example, in terms of pollution and health indices). Similarly, such technologies are needed to monitor, and assess the state of increasingly diverse, complex and interacting technical systems and system-of-systems including green buildings, advanced energy and transport systems, water production and waste treatment plants, flexible and high value manufacturing facilities and entire eco-cities.

Any threats, faults and failures (both impending and occurring) have to be quickly prognosed and diagnosed, followed by recommendations on necessary corrective actions.

2.2.2 Control, manage and optimise

These interactions with public sector agencies beyond the economic development objective is something relatively new to A*STAR, but is important for this research theme, as the activities of government and public sector have a great impact on how industry develops technological products and solutions.
Technical systems not only need to be correctly planned and designed, they have to be properly operated, maintained, controlled, managed and optimized to derive maximum efficiency and benefits from their use.

The monitoring and assessment of complex systems and system-of-systems that support and sustain economic activities and human communities, have been discussed earlier. Such activities and technologies are also pre-requisite and critical to the efficient management and optimizing of resources and complex engineering systems that are key to sustainable development.

Bi-directional flows of data/information, energy/power and materials are needed to achieve maximum efficiency and improved functionality of complex systems. A recent example is in the area of smart grids that utilize advanced info-comm technologies to manage and optimize the interactions among what used to be separate groups of suppliers and end-users. As part of smart grids, sophisticated control, management and optimization techniques and technologies are needed to integrate electric vehicles into the power system, as challenges are posed by both the supply of power from the grid (charging) and potential supply of power to the grid (vehicle to grid, with the vehicle’s batteries acting as a storage system).

Innovations and advances in computer-based tools and info-comm technologies (ICT) will play a critically important role in this area, enabling fast and effective data processing, transfer, and analysis, followed by modeling, simulation and intelligent management and decision support based on timely and relevant data, information and knowledge.

2.2.3 Conserve (reduce consumption), replace, diversify and adapt

Sustainable development will be enhanced if the world is able to conserve, replace, diversify and adapt in relation to scarce and depleting natural resources. Thus, R&D to develop and utilise alternative and sustainable sources of energy (including solar, wind, bioenergy and hydro), fuels, chemicals and materials are critically important, to replace and diversify from unsustainable resources such as fossil fuels and minerals and to reduce carbon emissions.

Developing and utilising a gamut of cost-competitive renewable resources (e.g. renewable energy, plants and other biomass feedstocks), utilizing advanced materials (including nano-materials and structures), chemical and biotransformation processes (sometimes mimicking natural processes) provide huge potential to enhance sustainability.

Beyond resources (supply-side), technologies should be developed for at the demand/end-user side that contribute to conservation, replacement,
diversification and adaptation. For example, electrification of the transport sector can lead to reduced demand for petroleum-derived fuels such as petrol and diesel. Instead, renewable energy, and other alternative energy resources such as natural gas, nuclear, clean coal, can be utilized to power the transport sector through the use of electric vehicles. Successful electrification of vehicles can only take place through technological advances in electrical energy storage, with batteries and ultra-capacitors currently providing the greatest potential and promise.

2.2.4 Prevent and reduce adverse environmental impacts (including production of greenhouse gases)

Mankind’s population growth and economic activities in pursuit of higher standards of living have created huge environmental problems including pollution of land, water and air. Environmental impacts can be prevented and reduced through technological innovations that

- Enable avoidance of pollution (e.g. by improving the cost-competitiveness of renewable energy technologies)
- Reduce pollution (e.g. by improving energy efficiency across multiple economic and industry sectors, including residential, commercial, industrial and transport sectors)
- Neutralise pollution (e.g. developing cost and energy-efficient after-treatment technologies for local pollutants such as particulate matter, SOx, NOx, and technologies for capture, storage and utilization of CO2)

2.2.5 Re-use, recycle, re-mediate and recover

Rising affluence, growing consumerism, shorter product life, and population growth in tandem with limited and depleting natural resources such as fossil fuels and minerals mean that there is a compelling need to avoid and reduce waste from economic activities. Technologies that enable cost-effective re-use (including re-manufacturing), recycling, re-mediating, and recovery of waste, are needed to enhance sustainable development, by effectively making waste a resource in manufacturing and other activities. Solid and liquid waste can be used to derive useful energy, materials, chemicals and even products. Such waste management technologies and activities are most effective if they take into account broader-based ecosystems that involve multiple industrial sectors and activities (through “industrial ecology”).
2.3 Capturing and adding economic value

As mentioned in the introductory chapter of this report, there is now increased recognition that substantial economic value can be captured and added through development of technological products, services, and solutions that enhance sustainable development.

Numerous market reports point to very high growth rates in various industry sectors directly related to the technological areas of interest under Sustainable Development.

For example, a study by New Energy Finance on behalf of the UNEP’s Division of Technology, Industry and Economics (DTIE) indicated annual growth rates exceeding 50% in the sustainable energy area over the period 2004-2007 (see Figure 2.1).

![Figure 2.1 – Total new investment in sustainable energy (2004-2007)](image_url)

Note: Grossed-up values based on disclosed deals. The figure represents total new investment in clean energy only, and so excludes investor exits made through public market offerings, PE buy-outs, and acquisitions of projects and companies. Total value is adjusted for reinvestment. Geared reinvestment assumes a 1 year lag between VC/PE/Public Markets funds raised and reinvestment in projects.

Source: New Energy Finance

Source: Global trends in sustainable energy investment 2008, Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency, commissioned by UNEP’s Division of
In its latest Clean Energy Trends report (2009), Clean Edge, a leading research and publishing firm that helps companies, investors, and policymakers understand and profit from clean technologies, projected that biofuels, solar, and wind along would grow into a US$325 billion clean energy cluster by 2018 (see Figure 2.2).

In Singapore, the Economic Development Board\textsuperscript{10} has identified the cleantech industry (comprising clean energy, environment and water sectors) as a strategic economic growth area, and has committed to developing the industry and creating new jobs. Recent successes in these efforts include huge investments made in solar PV manufacturing and other clean energy areas, that are expected to create 7,000 jobs and contribute SGD$1.7 billion (USD$1.1 billion) to Singapore’s gross domestic product by 2015.

![Figure 2.2 – Global Clean Energy Projected Growth 2008-2018\textsuperscript{11}](image)

Technology, Industry and Economics (DTIE) under its Sustainable Energy Finance Initiative and was produced in collaboration with New Energy Finance Limited.


\textsuperscript{11} Clean EnergyTrends 2009, Joel Makower, Ron Pernick, And Clint Wilder, Clean Edge, March 2009
The water sector should see its value-added contribution to the GDP rise from SGD$0.5 billion (US$0.3 billion) in 2003 to SGD$1.7 billion (USD$1.1 billion) in 2015, with a doubling of jobs in this sector to about 11,000. The country is already home to big names such as General Electric of the US, Nitto Denko of Japan, Siemens of Germany and Veolia of France, while homegrown champions include Hyflux, which plans to build the world’s largest seawater desalination plant in Algeria and SembCorp Environmental Management, the largest waste management company in Southeast Asia.

2.4 Recommended programmes

The Sustainable Development panel adopted the Siemens’ Picture of the Future (PoF) process to identify research programmes that could be recommended under this theme. Based on the PoF methodology, the panel’s scope and the associated trends and drivers were identified.

A preliminary identification and evaluation of different alternative technologies and innovations that could potentially be important to sustainable development was first conducted, based on:

- the user segments they served (this was the main factor used to organize the technologies of interest)
- their relationship/relevance to trends and drivers
- the service/ functions they provided to the end-user, and the
- the living spaces they were deployed in

Sub-groups were formed to assess innovations and technologies in more detail and these were verified with potential relevant users.

Potential programs were then identified based on the clustering of technologies in related areas. The final set of technologies and innovations were then decided for each of these programs.

A set of criteria was then used for prioritization of these potential programs, involving factors such as:

- Size (in terms of resources needed)
- Cross Discipline
- Use-Oriented (User Validated)
- Economic Impact
- National Interest
- (SERC) Niche with respect to other organizations performing sustainable development R&D
The seven programs selected for recommendation under the Sustainable Development theme (and summarised in the Figure 2.3\textsuperscript{12} below) are

- Waste Management
- Sustainable Manufacturing
- Sustainable Fuels, Chemicals and Materials
- Solar PV
- Green Buildings
- Energy Storage
- Intelligent Eco-city Infrastructure & Systems.

\textsuperscript{12} The figure includes consideration of the overlaps that could potentially occur among the different programmes
Chapter 3
Proposed Programmes

3.1 Programme on Waste Management

3.1.1 Programme Description

Countries in ASEAN and Asia are developing rapidly. As societies become more affluent, their material consumption rate escalates and waste volume in turn increases. In the Global Waste Management Report, it was stated that in 2006 the total amount of municipal solid waste generated was 2.02 billion tonnes, representing a 7% annual increment from 2003. Waste is generated in a number of forms across various sectors (e.g. residential, commercial, and industrial) and can adversely impact the environment. Waste management is therefore a significant emerging industry to develop to ensure sustainable development. This programme proposes to look at waste management holistically from both the technological and systems aspects.

Waste is presently at the end-of-life (EoL) of every product/process and there are various options at EoL stage. Figure 3.1 below shows the general EoL hierarchy.

![End of Life (EoL) Hierarchy](image)

Figure 3.1 - End of Life (EoL) Hierarchy

The hierarchy presented in Figure 3.1 has arranged the higher value and lower environmental burden activities towards the apex of the pyramid while the reverse would be true towards the base of the pyramid. Disposal is the presently
the most common approach but one which unfortunately provides little benefit in terms of sustainability. This programme does not address the three levels nearest the pyramid’s apex as these are typically covered in standard manufacturing operations13. The focus of this programme will be on the three levels closest to the pyramid’s base with the intention of bringing about technological breakthroughs leading to higher value resource reclamation at lower costs and overall reduction in disposal.

3.1.2 Programme Components

The Waste Management programme will comprise the following components:

3.1.2.1 Solid Waste Management

- **Waste sorting and separation technologies**

  Because waste is a mixture of materials, recovery of specific materials can be a difficult undertaking. This feature has been a significant restraint on wider practice of resource reclamation. As sorting at source is usually not very successful due to lack of space and possibly hygiene concerns, integrated collection is commonly practiced. Sophisticated sorting technology with higher resolution than existing systems is needed to improve resource recovery rates and recovered resource quality. Separation technology to recover precious metals, ferrous, and particularly non-ferrous metals, such as zinc and nickel, is needed.

- **Waste collection system**

  Collection of waste which is difficult to handle (e.g. decomposable and odorous) is another area of concern. An example is an easily decomposable organic waste such as food waste. In order to improve the collection coverage and hence collected fraction, and so improve the economics of food waste collection and resource reclamation, novel systems for storage and transport which improves ease of handling and minimization of decomposition (and hence odours) will be needed.

  Liquids associated with solid waste (e.g. food waste) are particularly challenging. Moisture increases the weight of waste and where this flows from the waste is typically very polluting and odorous. The challenge will be to develop technologies which can separate moisture from the waste in an energy efficient manner.

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13 The proposed Sustainable Manufacturing Programme under this theme covers some of the issues in the levels closer to the pyramid apex.
• **E-waste recycling techniques**

E-waste is one of the fastest growing components in waste from the residential and industrial sectors and is expected to double in the next few years. Currently the most common practice is to recover only the precious metals and dispose of the remaining components. The programme will support research into identification of useful materials beyond the precious metals and recovery of these while appropriately managing the hazardous substances present in e-waste.

In addition to the huge amounts of e-waste from electronic appliances and products, the recent upsurge of interest in electrical storage and electric vehicles can result in another important source of e-waste from batteries that reach the end of their useful life.

• **Waste to product**

Waste to products consists of three focuses namely, recycling of common materials such as plastics, glass and metals, recycling of inorganic industrial waste/effluent such as sludge and incinerator bottom ashes and recycling of organic waste.

There are already existing technologies for recycling common materials such as plastics, glass and metals but these are typically still at relatively low technological levels. The challenges and opportunities are to improve the efficiency of the processes and to improve the quality and hence value of the materials recovered to prevent or slow down the effect of downcycling. Converting these wastes to feedstock through chemo-biotechnological means is potentially exciting.

Recycling of organic waste has two applications for products in general. The recycled organic material can be made into biodegradable materials for packaging and other daily consumer products; they can also be made into compost and fertilizers to be returned to the agricultural and horticultural sectors to restore texture and nutrients to the soil. In the Singapore context, technologies for conversion of ligno-cellulosic wastes from horticultural activities into useful products can be interesting.

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14 Singapore has recently announced the formation of an Electric Vehicle Task Force, and has signed agreements with EV manufacturers and EV power infrastructure providers to launch a EV testbed in Singapore.
Recycling of inorganic industrial waste/effluent such as sludge and incinerator bottom ashes has to consider the presence of hazardous substances, inconsistencies in quality from different batches, and the complexities of processing such materials into useful and safe products. Nevertheless the quantities of sludges and incinerator bottom ashes are set to increase and applications and technologies shall need to be developed to expand recycling of these materials.

- **Waste to energy**

  All waste to energy processes that have the potential for deployment at an economically viable scale are included here. Examples include the various types of biomass conversion such as ligno-cellulosic based fuels, alcohol, methanation, and hydrogen production. The main challenges in this area will be improvement in conversion efficiency, engineering and system integration. As an example, biogas can be separated into methane and carbon dioxide. The methane can be used to drive fuel cells while the carbon dioxide can be converted to methanol. Another example of system integration can be recovery of steam at the incineration plants to drive other processes.

### 3.1.2.2 Liquid Waste Management

- **Water Reclamation from Wastewater**

  The areas of focus in liquid waste management are water reclamation and reducing the energy needed to treat the wastewater. In the current process of wastewater treatment (prior to reclamation), a large amount of energy is needed for aeration. The focus shall be on technologies that can improve the efficiency of recovering energy from sewage through pre-concentration of the as-received sewage. The other areas of interest include forward osmosis for wastewater pre-concentration and water reclamation and membrane distillation for desalting. These have potential for lower energy requirements.

- **Chemical recovery and treatment**

  Any applications and technology development that can facilitate recovery of chemical baths (as in electroplating) for further or other beneficial uses instead of disposal shall be considered. Failing such recovery, research

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15 This research area may have some overlap with proposed areas under the Sustainable Fuels, Chemicals, and Materials Programme.
on treatment of these chemical baths for safe disposal at a lower cost will then be needed.

3.1.2.3 Integrated Waste Management Systems

Different kinds of waste are produced in small quantities at most locations and due to this, most of wastes are mixtures and treated as general municipal waste. Scientifically designed waste management systems with a focus on 3Rs (reduce, reuse, recycle) are in demand. Efficient systems which can bring about savings in waste management through increase in earnings from recovered materials and savings from optimally managed (and reduced) incineration and landfill disposal should be developed under this programme. These systems should maximize resource recovery volume through resource augmentation.

A component of this programme should be the mathematical modeling (and visualization) of the systems used or proposed for waste management before implementation and thereafter for better management of the implemented systems. This would likely require enabling industrial ecology through information system support such as the incorporation of IT/embedded systems where information on the waste management operations can be stored and exchanged. Other decision making tools and sustainability assessment tools will also be useful.

3.1.3 Economic and Technological Impacts and Opportunities

Over the years, Singapore has developed a very efficient and effective waste management system. Notwithstanding this, there is a long term environmental sustainability issue arising from space constraints and hence lack of space for landfilling. This coupled with the fact that Singapore is deficient in natural resources (which has to be imported but is being rapidly depleted at source – e.g. fossil fuels) the need to recover resources from waste becomes more pressing. The argument, going forward, should then be “waste is a misplaced resource” and beyond altruism and environmental welfare - there is “brass in the muck”.

The EDB has estimated that the global CleanTech market is expected to grow at 10-15% per annum over the next few years. With the new opportunities and technologies developed under this programme, it will increase the availability of recovered materials and resources thus driving new economic activities. These resources, if not recovered would end up in landfills, generating negative value as disposal costs will be incurred. Giving value to these resources will imply that new jobs can be created, an international "resource from waste" exchange
market can be developed and SMEs can be set up to be the end solution providers eventually to sell the technologies developed locally and internationally.

**Potential to leverage on user segments in Singapore to validate or demonstrate technologies**

Given the compact and highly urbanized nature of Singapore, it is an ideal site for use as a test bedding and early technology adoption location. It has been estimated that by 2030 two thirds of the world population will live in urban centres. This means there are 1 million additional city dwellers each week. These urbanites will generate an estimated 10 million tonnes of refuse daily. Thus solutions for integrated urban waste management will be important both for environmental sustainability and as a growth industry. Singapore, a city with high population density and good infrastructure, will be a good candidate as pilot city for any pilot-scale integrated systems to be built and trailed.

**Other competitive advantages for Singapore**

Waste management in developed countries typically accounts for 10% of the overall cleansing budget (mainly collection). There is thus scope for expansion and innovation in waste management technologies as applications expand. Singapore has opportunity to serve as a major waste management and recycling technologies exporter while simultaneously addressing its own problem of space constraints for more landfill and incinerator plants.

Waste management contributes to a clean and safe environment which is conducive and attractive for foreign talent and foreign investments to relocate to Singapore.

### 3.1.4 Assessment and stocktake of R&D capabilities

**Local Capabilities**

<table>
<thead>
<tr>
<th>Programme / Initiatives /Capabilities</th>
<th>Programme / Initiatives /Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>A*STAR Institute of Chemical Engineering Sciences</td>
<td>Industrial Biotechnology Programme - Waste to Energy capabilities</td>
</tr>
<tr>
<td>Nanyang Environment and Water Research Institute (NEWRI)</td>
<td>- Advanced Environmental Biotechnology Centre (AEBBC)</td>
</tr>
</tbody>
</table>
Overseas Capabilities

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Focus Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Nations International Environmental Technology Centre</td>
<td>Sustainable production and consumption</td>
</tr>
<tr>
<td></td>
<td>Water and sanitation</td>
</tr>
<tr>
<td></td>
<td>Focus on waste management</td>
</tr>
<tr>
<td>International Solid Waste Association</td>
<td>All aspects of solid waste</td>
</tr>
<tr>
<td>European Topic Centre on Sustainable Consumption and Production</td>
<td>Waste</td>
</tr>
<tr>
<td></td>
<td>Resource Use</td>
</tr>
<tr>
<td></td>
<td>Life Cycle Assessment</td>
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<tr>
<td></td>
<td>Sustainable Production and consumption</td>
</tr>
<tr>
<td></td>
<td>Material Flow Accounting</td>
</tr>
<tr>
<td>Veolia Environment (France)</td>
<td>Veolia Environmental Services</td>
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<tr>
<td></td>
<td>Veolia Water</td>
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<tr>
<td>Visy (Australia)</td>
<td>Waste Material sorting</td>
</tr>
<tr>
<td></td>
<td>Material recycling</td>
</tr>
</tbody>
</table>

3.1.5 Recommended programme roadmap and milestones
As waste management is large scale in nature, it is proposed that the programme duration to be 5 years with two phases. The first phase would involve the research portion where basic technicalities are being solved before moving into the second phase of testbedding portion where system level issues relating to integration are being tackled. One major milestone should be the achievement of a targeted efficiency to be able to fit into a prototype system before the actual testbedding.
3.2 Programme on Sustainable Manufacturing

3.2.1 Programme Introduction

Sustainable manufacturing is aimed at producing products at competitive time, cost, and quality with minimum or no negative impact to the environment. The ultimate goal is to achieve zero emissions and wastes in manufacturing. As manufacturing is a major contributor to environmental pollution, greenhouse gas emissions, and waste, achieving sustainable manufacturing is deemed crucial in achieving sustainable development.

![Figure 3.2 - Traditional Manufacturing – Linear Processes](image)

Traditional manufacturing (Figure 3.2) is a linear process. There are many types of wastes generated during manufacturing. The wastes are either discharged (e.g., liquid types or gasses) or sent for incineration/landfill (solid types). Likewise, the products at the end-of-life stage are also typically disposed for incineration of landfill. These practices deplete non-renewable resources, and cause damage to the environment.

![Figure 3.3 Sustainable Manufacturing – Closed Processes](image)

Sustainable manufacturing (Figure 3.3) aims to achieve closed-loop processes throughout the life cycle of the products from raw materials making, manufacturing, use till disposal. Through clean manufacturing technologies, the wastes and emissions in manufacturing are minimized, and wastes generated as well as the end-of-life products are considered as valuable resources. They are
either recycled into raw materials, reused in products, remanufactured to like-new products again, or if appropriate, converted into energy (e.g., biomass) or disposed in environmentally benign forms.

To realize sustainable manufacturing, innovative technologies for clean manufacturing must be identified and developed. This involves interdisciplinary and long term effort. It is also an area that has the tremendous potential for the development of new and high value manufacturing industry in Singapore. In fact, it is believed that technologies that enable clean manufacturing will shape the future manufacturing industry and will be on high demand.

3.2.2 Programme Objective and Scope

The objective of this programme is to build fundamental and cross-disciplinary capabilities in sustainable manufacturing research, and develop selected clean manufacturing technologies that are deemed:

• strategic to Singapore’s manufacturing industry,
• with high commercial value,
• having the niche advantages, and
• requiring expertise/resources across SERC RIs.

The scope of the programme is to focus on the development of an integrated set of system-based enabling technologies that are critical to achieving sustainable manufacturing. Specifically, the following four areas of research are proposed (Figure 3.4):

• life cycle engineering based tools and studies for sustainable product and process design and for the development of critical sustainable manufacturing technologies,
• industry ecology map of Singapore to support the paradigm change towards sustainable manufacturing,
• Wastes-to-products/energy (W2PE) technology map for accelerating the implementation, as well as the research, of sustainable manufacturing technologies in Singapore, and
• strategic areas that are fundamental to a sustainable manufacturing industry e.g. sustainable packaging and remanufacturing
3.2.3  Key research Areas

3.2.3.1  Life Cycle Engineering based Tools and Studies

To be meaningful, sustainability has to be measured on the basis of a global eco-system perspective. This requires that considerations should cover the entire life cycle ranging from materials, fabrication, usage, and end-of-life of products/services. Life Cycle Engineering (LCE) methods and tools are hence essential in the conceptualization, design, and development of products, processes, and clean technologies for sustainable manufacturing.

In the content of this proposal, LCE basically include life cycle cost (LCC) modeling and analysis, life cycle assessment (LCA) for environmental impacts, sustainability metrics/indicators, and multi-dimensional decision-supports.

LCA is an internationally standardized methodology (ISO 14040 series). LCAs help to quantify the resources consumed and the potential environmental impacts of goods and services (products). The entire life cycle is taken into account, including the provision of raw materials, energy, as well as the end-of-life stages irrespective of when or where the activities occur. Environmental and health impacts as well as resource scarcity are quantified in terms of indicators.
Indicators are typically provided for climate change, cancer effects, land use, and others.

These methods and tools are required for measuring, on per product or company basis, the Greenhouse Gasses (GHS) emissions and the resource (energy, water, raw materials, etc.) efficiency. They also provide a means to quantify the life cycle cost for better visibility and optimization of cost profiles over the life cycle processes of a technology and product. These are all basic measures for sustainability, and hence essential for achieving sustainable manufacturing.

Firstly, these measures will scientifically prove if a technology/product is really sustainable. Secondly, understanding the quantify and distribution of life cycle cost and environmental impacts of a technology/product will reveal the major areas requiring improvements and hence help to identify technologies and set the technical targets/specifications that would minimize the costs or impacts with economical benefits.

These measures also provide the essential base for decision making in the design of green products and manufacturing processes that are energy and resource efficient with minimum or zero emissions and wastes. The decisions would cover selection of materials, logistics, manufacturing processes, usage models, and ways of disposal. Normal LCA studies take months, if not years, to complete. However, design decisions for all possible options need to be evaluated, ideally, in hours if not minutes.

At present, LCE methods and tools require extensive modeling and life cycle inventory data, and are not adequate to support the exploding activities on sustainable technology, products, and service innovations. Research efforts are required to develop approaches, indicators, reference data, and reference models. With the results, a breakthrough has to be achieved in LCA methods coupled with an integrated database and system for life cycle based design support in product and process design. Specific areas of research include the

- Life cycle assessment of clean energy technologies (biomass, carbon capture, smart grid, etc.)
- Risk assessment of nanotechnologies for lightweight materials (resource and energy efficiency, human health)
- Quantification of carbon footprint of major manufacturing processes
- Quantification of costs from environmental impacts
- A database and system tool for life-cycle based decision-support in green product and process design
Pilot studies and cross-discipline collaborations are needed to develop, apply, and commercialize specialized toolkits for industrial applications as well as for the effective development of sustainable manufacturing technologies.

This area of work requires knowledge and specializations from following disciplines:

- Industrial Engineering
- Materials engineering
- Chemical engineering
- Mechanical engineering
- Environmental engineering
- Bio-engineering

**Deliverables** of the research will include a set of methods and tools, databases, established core competence and facilities, and a certified and internationally reputable laboratory for cost and carbon footprint quantification, labelling, environmental impact assessment of new technologies/products, and green product/process design and development.

### 3.2.3.2 Industrial Ecology Map and Waste-to-Products/Energy Technology Map

Wastes are inevitable in manufacturing activities. Minimization of wastes by a particular company or industry can be achieved to a certain degree. To realize the goal of zero emission and wastes, however, it is necessary to develop industrial ecosystems for recycle, reuse, and resource conservation.

In an industrial ecosystem, industries are interconnected through mass and energy streams for mutual benefit. It converts the industrial process from a linear process to a cyclic process where the waste generated by one industry can be used as a resource by another industry.

While Singapore may be resource scarce, due to intensive business and manufacturing activities, Singapore is rich in wastes. According to Ministry of Environment and Water Resources, a total of 5.97 million tons of waste was generated in 2008, an increase of 6.6% over the previous year. Of the total, 56% are recycled, 41% are incinerated, and 3% are landfilled. The recycle rates for many valuable commodities are low: glass (18%), food (12%), textiles (12%), plastics (8%), and e-wastes (3%). Of the recycled, most are primitive with low value-add.

In addition, there are huge amount of “by products” which are not categorized under waste, but are effectively exported as low value resources. For example, the wheat floor production of Prima Group Ltd produces more than 40 tons/day
bran, and exported to Malaysia/Middle East as low grade animal feed. In the meanwhile, local biodegradable packaging manufacturers have to set up their factories overseas due to available raw materials from agriculture residues. The development of packaging and other high-value materials/products from the bran would create significant extra-values as well as new companies in Singapore.

We propose two aspects of research in this area:

- **Industrial Ecology Map of Singapore:** This work is to identify the types and quantity of wastes and major input-materials by major industries in Singapore, and upon which to create an eco-system model of the current industries. Through simulation, analysis, and optimization, a to-be eco-system would be developed that will guide the planning and implementation for waste minimization. In the energy aspect, the eco-system will cover major demands and producers of heat and steam in addition to potential renewable energy sources from wastes. This will provide a good matching of steam and power demand, facilitating the use of cogeneration and trigeneration amongst our industry. This will help to relevant industries, e.g., power stations to significantly improve their energy efficiency. It is envisaged that the realization of such an eco-system would drastically increase the resource efficiency, reduce costs and carbon footprint, and create high value-add to the manufacturing industry.

Singapore’s small geographical size coupled with a high diversity of industries offer a unique base for the research. Riding on the world wide trend of eco-city development, this work would have tremendous opportunities to develop expertise and IPs for world market.

- **Wastes-to-Products/Energy Technology Map:** This aspect of work is to research into the trends and state-of-art technologies that convert wastes and “by-products” to high-value materials, energy and other forms of products. A major focus will be the biomass (wood/timer, paper/cardboard, horticultural wastes, food, textiles/leather) which accounts for a total 2.42 million tons in 2008 excluding by-products like bran. The other options include plastics (680,000 tons in 2008), e-wastes (close to 300,000 tons in 2008), and glass (60,000 tons in 2008).

There is intensive research in this area world wide. The potential is far from being reached. The Technology Map will support the fast implementation of the best available technologies in the industry as well as the development of such technologies in Singapore. As a nation without natural resources and
with a deep concern for resource security, this area of research should be strategic to Singapore.

This area of work requires knowledge and specializations from following disciplines:

- Industrial Engineering,
- Materials engineering
- Chemical engineering
- Mechanical engineering
- Environmental engineering

**Deliverables** will include

- an *Industry Ecosystem Maps* of Singapore (both as-is and to-be), and
- a *Technology Map* summarizing the state-of-art technologies and trends in wastes-to-products/energy for both other research programmes/projects and industrial implementation for the realization of Ecosystems.

### 3.2.3.3 Remanufacturing

Remanufacturing is a solution to waste reduction in manufacturing. It is a process to convert used products to like-new condition. The like-new condition is not only up to its original specification at the time of manufacturing, but also to the present day requirements.

Remanufacturing stands out as a preferred option due to many inherited attributes. It conserves most of the energy used in the manufacturing of the components. In most cases, it is at a much lower cost comparing with manufacturing new components. Moreover, there is an increasing demand for re-manufactured products, especially when the products are offered with warranty like new products or guaranteed effective usage hours under product-as-service business models.

Leading companies in jet engines, airplanes, ships, heavy machinery, and copy machines, just name a few, have already taken remanufacturing as a core competence.

Many new opportunities for technological innovations exist with enormous economical and environmental potential. Included are

- the technologies for assessment of component conditions,
- fuzz or self-learning decision-support systems,
- special re-manufacturing processes, and
- automation of the largely manual processes in today’s remanufacturing plant.
Another technological challenge comes from targeting at products with shorter life cycle, such as handphones and other electronics products. Comparing with recycling e-wastes for raw materials, re-manufacturing is clearly a much better way. The need is in breakthrough of design-for-remanufacturing and relevant remanufacturing technologies/equipment.

Singapore has unique advantages in remanufacturing due to its geographical location in Asia, widely-linked sea and air transportation network, highly efficient logistics system, and a comprehensive structure of supporting industries and expertise. In this regard, Caterpillar's decision to set up its Asia remanufacturing plant in Singapore is a testimony.

By becoming a leader in remanufacturing technology innovation, a new sector of manufacturing industry can be developed in Singapore.

While this area may be relatively new to SERC, we have well-established capabilities and facilities for the research and development of remanufacturing technologies. These include:

- Materials engineering
- Chemical engineering
- Metallurgy
- Manufacturing processes (forming, joining, coating, machining)
- Automation (robotic, vision inspection/control, equipment)
- Systems (artificial intelligence, sensor/monitoring, operation research)

Deliverables will be a set of enabling technologies, namely,

- the technologies for assessment of used component conditions with self-learning decision-support capabilities;
- a methodology for developing remanufacturing strategies for a given type of products (mechanical, electrical/electronics, with short to long product life cycles), including design for remanufacturing, knowledgebase for remanufacturing processes, and optimization tools for remanufacturing strategies.

3.2.3.4 Sustainable Packaging

Packaging is required for the protection and transportation of industrial and consumer products. However, packaging materials are often used just once, resulting in the generation of large quantify wastes. In 2002, the European Union estimated packaging makes up roughly 17 per cent of its municipal waste stream
(by weight)\textsuperscript{16}. Packaging is also an essential part of products. Resource efficiency and waste reduction in packaging make direct contribution to green products. Achieving sustainable packaging has become increasingly the concern worldwide.

Sustainable packaging is the development and use of packaging which results in improved economical value and ecological footprint. The goals are to improve the long term viability and quality of life for humans and the longevity of natural ecosystems. The challenge of sustainable packaging is that it must meet the functional and economic needs of the present without compromising the ability of future generations to meet their own needs.

Of the many potential topics, the following areas of research in sustainable packaging are proposed:

- The development and application of biodegradable polymers for packaging
- The development of barrier coatings, tiered or layered polymer processing technologies
- Packaging as services

\textbf{Deliverables} will include

- \textbf{Design and process technologies} for economically viable and environmentally benign biopolymer-based packaging; and
- \textbf{A universal model for packaging-as-services analysis}.

\subsection*{3.2.4 Pilot Applications and Economic Impact}

The pilot applications of developed technologies under this programme will be targeted on establishing pilot successful cases in selected industry sectors, including, but not limited to, the following:

- Food manufacturing
- Electronics manufacturers (MNCs, Contract Manufacturers)
- precision engineering (moulding, mould/die, equipment)
- Sustainable development (waste management, recycling solution providers, renewable energy producers, etc.)

The industry ecology map will be used to guide the selection of cases across the industry sectors. The aim is not only on successful cases of individual

companies, but more importantly, the inter-connections of these cases under the futuristic industry ecology. These cases will provide the needed examples and understanding for Singapore’s manufacturing industry to be a leader in the paradigm shift towards low-carbon sustainable manufacturing. Such a leadership will greatly advance the industry's global competitiveness and provide tremendous opportunities for the development of new and high-value manufacturing in Singapore.
### 3.2.5 Existing R&D capabilities

**Table of local R&D capabilities in Sustainable Manufacturing, including Research Institutes and Institutes of Higher Learning**

<table>
<thead>
<tr>
<th>Institution/Centre</th>
<th>Theme</th>
<th>Research Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMTech</td>
<td>Nanoparticle based Catalyst/Materials</td>
<td>Biodegradable polymeric nanocomposites; Lead-free Solder Nanocomposites; nanoporous catalysts; High performance nano catalysts for producing clean fuel; nanonickel catalyst; Nanomaterials for energy conversion and storage; gold-coated nanoparticles for conversion of solar energy to chemical energy; Hollow nanostructured semiconductor materials synthesis as photocatalysts for production of hydrogen from water and degradation of organic pollutants in waste water</td>
</tr>
<tr>
<td>Nanoscience and Nanotechnology Initiative (NUS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Department of Chemical and Biomolecular Engineering (NUS)</td>
<td></td>
<td></td>
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<tr>
<td>School of Physical &amp; Mathematical Sciences (NTU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>School of Chemical &amp; Biomedical Engineering (NTU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICES</td>
<td>Green Chemistry &amp; Materials</td>
<td>Low temperature catalytic combustion of formaldehyde; Visible light driven photocatalyst; Fabrication and catalysis of PEM Fuel Cell; Oxidative desulphurization for ultra clean fuels; Synthesis of hydrogen peroxide directly from hydrogen and oxygen</td>
</tr>
<tr>
<td>School of Physical &amp; Mathematical Sciences (NTU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICES</td>
<td>Renewable Feedstock Utilization &amp; Conversation</td>
<td>Processing Fatty Acid Esters; Glycerol conversion and upgrading; Polyatic Acid: Development of new catalysts, block copolymers and nanocomposites; New Generation of Biodiesels; Conversion of bioethanol to chemicals; Production of biodiesel, bioethanol and lactic acid from biomass; Microbial construction &amp; conversion to high-value products, biogas and organic acids; Renewable materials;</td>
</tr>
<tr>
<td>School of Civil and Environmental Engineering (NTU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIMTech</td>
<td>Degradable Materials</td>
<td>Biopolymeric materials development; Sustainable Packaging; Application development of biopolymers; Biocomposites; Biodegradable Artificial Materials; environmentally sustainable adhesives; Biodegradable shipping materials</td>
</tr>
<tr>
<td>Minerals, Metals &amp; Materials Technology Centre - M3TC (NUS)</td>
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</tbody>
</table>
### Eco-efficient products and process designs

<table>
<thead>
<tr>
<th>Institution/Centre</th>
<th>Theme</th>
<th>Research Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMTech</td>
<td>Product Life Cycle Assessment and Design Tools</td>
<td>Eco-Lifecycle Cost Optimization; Life Cycle Assessment; Toolkits for Sustainable Design and Manufacturing Decision Support; Carbon footprint; Tools for systematic waste minimisation</td>
</tr>
<tr>
<td>ICES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Research Centre (NTU)</td>
<td>Process Design for Environment – Minimal Manufacturing</td>
<td>Product creation, quality &amp; reliability, knowledge management; Optimal, integrated product and package design; Development of environmentally-friendly products, packages and their related processes; Sustainable Mass Customization; Environmental Friendly Modularity</td>
</tr>
<tr>
<td>Design Technology Institute (DTI)</td>
<td></td>
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</tr>
<tr>
<td>SIMTech</td>
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</table>

### Eco-efficient processing technologies

<table>
<thead>
<tr>
<th>Institution/Centre</th>
<th>Theme</th>
<th>Research Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMTech</td>
<td>Processing Technologies for Manufacturing</td>
<td>Machining with biodegradable lubricant; Laser Cladding &amp; Mould Repair; Recycling of light metal alloys; Recycling of plastics; Efficient manufacturing process; Net shape forming, casting and moulding process; Laser cleaning technology;</td>
</tr>
<tr>
<td>Laser Microprocessing Laboratory (NUS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical &amp; Aerospace Engineering (NTU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICES</td>
<td>Processing Technologies for Chemical/Pharma Manufacturing</td>
<td>Chemical process optimization for waste minimization; Surface coating alternatives to replace the environmentally unfriendly chrome plating process; Dry-lub4 for IC-moulding Applications</td>
</tr>
<tr>
<td>SIMTech</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>University</td>
<td>Research Initiatives</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>UK</td>
<td>Cranfield University</td>
<td>Centre for Sustainable Design</td>
</tr>
</tbody>
</table>
| UK      | Loughborough University | SMART Centre | - Sustainable design of product and processes for prevention and control of industrial pollution  
- Use of innovative materials  
- Energy efficiency and use of renewable energy in manufacturing  
- End-of-life management and product recovery/recycling  
- Information management and knowledge based systems to support sustainable manufacture  
- Cost benefit analysis in end-of-life product recovery  
- Industrially-led legislation and directives  
- Sustainability performance measures for monitoring the effectiveness of standards  
- Responsible marketing policies to encourage sustainable consumption  
- Innovative business models to support Sustainable Development |
| US      | Georgia Institute of Technology | Sustainable Design and Manufacturing Program | - Integrating cost, energy, and waste assessments  
- Reducing potential hazards in machining processes  
- Optimizing processes with the virtual factory  
- Developing environmentally-friendly products in less time  
- Improving process technology for remanufacture organizations |
<p>| US      | Rochester Institute of Technology, Golisano Institute of Sustainability | Remanufacturing Life cycle design Sustainable Energy Material recovery |
| US      | University of Michigan | Environmental and Sustainable Technologies | Science-based approach for Technology and Environmental Policy Design Sustainable Manufacturing Systems |</p>
<table>
<thead>
<tr>
<th>Country</th>
<th>Institution</th>
<th>Focus Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>Yale University</td>
<td>Green Chemistry</td>
</tr>
<tr>
<td>US</td>
<td>University of California, Berkeley, Consortium on Green Design and Manufacturing</td>
<td>• Environmental value systems analysis in semiconductor manufacturing&lt;br&gt;• Electronics recycling and end-of-life management&lt;br&gt;• Environmental impacts of telework, service industries&lt;br&gt;• Environmental supply chain management&lt;br&gt;• Industrial ecology&lt;br&gt;• Life cycle assessment&lt;br&gt;• Sustainable infrastructure</td>
</tr>
<tr>
<td>US</td>
<td>Massachusetts Institute of Technology</td>
<td>• Environmental analysis of manufacturing processes&lt;br&gt;• Product recycling systems&lt;br&gt;• Production, use and efficiency&lt;br&gt;• Benign and efficient materials</td>
</tr>
<tr>
<td>Sweden</td>
<td>Linkoping University</td>
<td>Remanufacturing, Product Service Systems, Sustainable Design</td>
</tr>
<tr>
<td>Sweden</td>
<td>KTH</td>
<td>Life Cycle Engineering, Sustainable Design, Eco-product development</td>
</tr>
<tr>
<td>Sweden</td>
<td>Chalmers University</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>Germany</td>
<td>University of Bayreuth</td>
<td>Remanufacturing, Service Engineering</td>
</tr>
<tr>
<td>Germany</td>
<td>TU Braunschweig Institute of Machine Tools and Production Technology</td>
<td>Energy Efficiency Monitoring Tools, Design for Recycling, Closed Loop Product Network</td>
</tr>
<tr>
<td>Germany</td>
<td>TU Berlin</td>
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3.2.6 Programme roadmap and milestones

Sustainable manufacturing is a relatively new cross-disciplinary research which is essential for the innovation of clean production technologies with high
commercial value. To develop a strong capability and commercializable results, we propose a 5-year programme (Figure 3.5).

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Figure 3.5 - Research Roadmap for Sustainable Manufacturing

3.3 Programme on Sustainable Fuels, Chemicals, and Materials

3.3.1 Programme Description

The bulk of fuels, chemicals, and polymeric materials are produced from crude oil by the petrochemical industry. The industry faces two major challenges: supply of crude oil struggles to keep pace with rising demand; and environmental pressures, including climate change concerns, are increasing. To address these challenges, industry must develop sustainable (environmentally benign, safe, and cost competitive) options to replace crude oil with alternative feedstock. Advanced processing technologies for alternative feedstock leading to lower cost and reduced green house gas emission can provide significant competitive advantages to major petrochemical hubs such as Singapore.

Oil, gas, and coal are likely to remain as the dominant feedstock in the next few decades (Figure 3.6). Technologies to replace oil with gas and coal such as syngas production and Fischer Tropsch Synthesis are competitive in special circumstances (e.g. cheap gas in Middle East) but require economy of scale and huge capital investments. By contrast, with the exception of ethanol production from sugar canes in Brazil, technologies to replace fossil feedstock with biomass
are not cost competitive and major breakthroughs are required to utilize non-food biomass.


**Figure 3.6 - World Marketed Energy Use by Fuel Types, 1980-2032**

This proposed “Sustainable Fuels, Chemicals, and Materials” programme divides the myriads of technologies under investigation by industry, universities, and government laboratories around the world into five sub-categories as follows:

- Development of alternative feedstocks
- Chemical conversion of alternative feedstocks
- Biotransformation of alternative feedstocks
- Carbon capture and utilization
- Biobased polymers and composites

### 3.3.2 Programme Components

#### 3.3.2.1 Development of alternative feedstocks

To diversify beyond oil and natural gas, Singapore needs to consider alternative feedstocks. Wastes are available locally but not in sufficient quantities to make a
substantive difference to meet demand\textsuperscript{17}. Available alternative feedstocks from Singapore’s neighbours include coal, palm oil, and various lignocellulosic biomasses such as rice straw, bagasse and empty fruit bunches from oil palm. Of these, coal and lignocellulose biomass are expensive to transport over long distance. Palm oil is easy to transport but it is a food crop and controversial. Three approaches to facilitate the supply of alternative feedstocks to Singapore are described below.

- **Conversion of coal to synthetic natural gas**

  Indonesia has abundant supplies of cheap and low quality coal which is expensive to ship and dirty to use. This coal can be readily converted to methane by gasification and methanation. The resulting synthetic natural gas can be transported to Singapore either by pipelines or by LNG tankers. The coal to natural gas technology is being practiced by Dakota Gasification in the United States. Coal gasification is still relatively expensive due to the use of expensive oxygen. Novel technology that can reduce the use of oxygen or lower the cost of air separation could make synthetic natural gas a clean alternative source of feedstock for Singapore.

- **Conversion of biomass to biooil**

  Non-food biomass is available in huge quantities in Southeast Asia. For example, Malaysia alone produces over 4 million tons of empty fruit bunches from palm oil production each year. However, the diffusivity and low density of biomass makes it expensive to transport. The conversion of solid biomass to a liquid called biooil can be carried out in relatively small scale economically by a fast pyrolysis process. Biooil can be produced at various point sources, e.g. palm oil mills, and transported to a central processing location, e.g. Jurong Island, for large-scale downstream conversion such as production of gasoline. Biooil is a complex mixture containing over 300 compounds. A thorough understanding of the pyrolysis process and how it affects biooil composition is essential for efficient and reproducible downstream conversions.

- **Energy crops**

  In this report, energy crops are defined as plants and microorganisms cultivated specifically for the purpose of producing feedstocks for the energy and chemical industries. Remarkable advances have been made in the application of biotechnology for producing biomedical and agricultural products. Major R&D efforts are now underway globally to apply industrial

\textsuperscript{17} Nevertheless, management and conversion of waste into useful energy and products are an important part of the Sustainable Development theme.
biotechnology to increase the productivities of energy crops as well as to modify their properties for more efficient downstream conversion. With strong existing capabilities in biology, chemistry, plant science, and process engineering, A*STAR is well positioned to contribute in this area of research.

Among energy crops, microalgae have attracted a great deal of attention because of its fast reproduction rates and ability to produce high contents of useful feedstocks such as lipids and glycerol. It has been projected that the productivity of microalgal oil could be 20 to 30 times higher than that of palm oil. As microalgae are generally not considered as a food crop, algal oil is a potential source of easily transportable feedstock for Singapore. However, to realize algal oil technology would require long-term research efforts due to a combination of significantly lower than projected oil productivities and high cost of production. The most important challenge is to develop a strain of algae that combines a high productivity of biomass and a high content of oil. This can be done by screening in nature or by genetic engineering. Unlike yeast and bacteria, genetic tools to modify microalgae have yet to be developed. Basic biological research of microalgae will have to be carried out to develop such tools.

3.3.2.2 Chemical conversion of alternative feedstocks

Environmentally benign and cost effective conversion technologies will have to be developed for using oil replacements such as gas, coal, and biomass. Chemical conversion technologies should be a preferred choice for Singapore because of its existing infrastructure and technological capabilities. Several key R&D challenges and opportunities are described below.

- **C1 processes**

C1 processes refer to conversion technologies involving single carbon molecules such as carbon monoxide and methane. Notable examples of demonstrated C1 processes include synthesis of gasoline from methanol and Fischer-Tropsch Synthesis of hydrocarbon diesel from syngas. Further cost reductions are required for these C1 processes to compete with existing oil-based processes, especially during periods of low oil price.

Conversion of syngas, a combination of carbon monoxide and hydrogen, is probably the most promising alternative to existing petroleum refining technologies based on crude oil. Syngas can be produced from gasification or reforming of natural gas, coal, and biomass. It can be converted to existing fuels and chemical building blocks as shown in Scheme 1. Production of syngas is still highly capital intensive and
requires innovations to compete with cheap oil. The cost of Fischer-Tropsch synthesis, FTS, can be further reduced by developing more active and selective catalysts to increase productivity and reduce reactor size.

Scheme 1. Syngas-based C1 processes

It is worth noting that hydrogen production via water-gas-shift reaction of syngas is also highly relevant to the refining of low quality crude oil with low H/C ratio and high sulphur content. Hydrogen is required for hydodesulphurization as well as to increase the H/C ratio needed in refined products.

Direct conversions of methane to single products with high yields are also highly desirable C1 processes. Methane conversions to ethylene and methanol with high selectivity at low conversions, respectively, have been demonstrated in the laboratory. However, to achieve high yields by combining high selectivity and high conversion is a formidable scientific challenge due to the greater reactivities of ethylene and methanol relative to methane. The direct conversion of methane to more stable benzene offers a better chance of producing a commercially viable high yield process. Highly efficient and selective catalysts are keys to develop direct methane conversion processes.

- **Biooil to gasoline**

In contrast to hydrocarbon-based crude oil, biooil is a complex mixture of oxygenates. Consequently, conversion of biooil to gasoline is significantly different and perhaps more challenging than refining of crude oil. Hydrogen will be required to remove the oxygen atoms in biooil as water. In addition, the size and shape of molecules have to be rearranged in a series of steps to meet the specification of existing gasoline. To develop a commercially viable process would require interdisciplinary research to
understand reaction mechanisms, invent highly efficient and selective catalysts, develop separation technologies, collect basic engineering data, and design the overall process.

- **Biobased platform molecules**

A number of biobased molecules have been coined as platform molecules by a DOE study based on their potential for making useful derivatives. Among them, lower alcohols from fermentation and glycerol from the production of biodiesel from vegetable oils have the greatest potential impact.

Biobased lower alcohols such as ethanol and isopropanol can be readily dehydrated to ethylene and propylene, two of the most important building blocks of the chemical industry, respectively. The viability of biobased olefins depends on the availability of low cost biobased alcohols.

Glycerol is notable because of its versatility in producing a variety of existing chemical products as shown in Scheme 2. The processes in Scheme 2 are being actively research and plans to produce propylene glycol from glycerol have been announced by ADM and BASF. Products derived from biobased feedstocks are potentially more environmentally benign and can provide marketing advantage. However, to be sustainable, they still have to be cost competitive.

**Scheme 2. Glycerol derivatives**

![Diagram of glycerol derivatives](image)

**3.3.2.3 Biotransformation of alternative feedstocks**
Biotransformation or bioprocess includes both whole-cell fermentation and enzyme-catalyzed processes. It can be applied to both natural and synthetic substrates. Notable commercial successes are fermentation of glucose to ethanol and enzyme-catalyzed hydration of acrylonitrile to acrylamide. The major advantage of biotransformation is its ability to carry out many reactions that are extremely difficult to do chemically. An outstanding example is the conversion of glucose to ethanol. Capital costs of bioprocesses are also generally lower than that of chemical processes because of mild process conditions. On the other hand, bioprocesses are disadvantaged relative to chemical processes due to generally low culture/product concentrations which increase separation costs and limited scope of reactions.

With its high quality biological and chemical research institutions, Singapore is well positioned to address these problems. The high biodiversity environment of Singapore also contributes to the chances of major breakthroughs.

- **Lignocellulosic ethanol**

The abundant supply and low cost of lignocellulosic biomass make it an attractive feedstock for producing ethanol. Being non-food matter, it is also a less controversial feedstock. The processing cost of cellulosic ethanol, however, is significantly higher than those of existing processes using sugar or starch. The current process of producing cellulosic ethanol as shown in Scheme 3 involves three steps: pretreatment to separate hemicellulose, cellulose, and lignin; enzymatic cleavage of cellulose to glucose; and fermentation of glucose to ethanol. A more environmentally friendly and cost effective pretreatment is needed to replace existing pretreatment processes. Current enzyme cost for breaking down cellulose to glucose is ten times higher than that of hydrolysis of starch. It needs to be brought down. Current fermentation technology can only metabolize glucose from cellulose to ethanol. Lignin poisons the yeast in fermentation. The C5 sugars derived from hemicellulose are difficult to ferment. As lignin and hemicellulose account for a significant portion of biomass in most lignocellulosic, finding value-added application for lignin and C5 sugars can significantly improve the economics of cellulosic ethanol.

Scheme 3. Lignocellulosic ethanol process
• **Fermentation of C1 substrates**

Syngas and methane are attractive C1 substrates for fermentation to high impact products. As described in the previous section, syngas can be readily obtained from gasification of gas, coal, and biomass. Conversion of syngas to ethanol with high selectivity is extremely challenging since it is a homologation process. Fermentation of syngas to ethanol has been reported but with low selectivity. Coupling gasification of lignocellulose with a highly selective syngas fermentation process is especially attractive because it can use 100% of the biomass.

Methane is available from natural gas or from fermentation of organic wastes as biogas. Natural strains of bacteria capable of metabolizing methane to methanol are known but the conversion is low due to methanol poisoning effect. Successful development of a genetically engineered microbe capable of producing high yields of methanol from methane would have huge impact, particularly for converting strained natural gas in remote areas into transportable methanol at low cost.

• **Conversion of platform molecules**

Useful chemical products can also be prepared from platform molecules by fermentation as shown in Scheme 2 in the previous section. An excellent commercial example is the DuPont process of making 1,3-propanediol, a monomer for polyester, from fermentation of sugar. The bioprocess competes very effectively against the chemical process developed by Shell which involves hydroformylation of ethylene oxide. Other promising bioprocess targets include C3 and C4 acids like lactic and succinic acid, and biodegradable polymers such as polyhydroxyalkanoate, PHA.

3.3.2.4 Carbon Capture and Utilization

• **Carbon capture and storage (CCS)**

CCS is a bridging technology to mitigate the effect of carbon emission from using fossil fuels in the next few decades. It is essential for using cheap and plentiful coal which has a large carbon footprint. It is most effective when applied at major point sources of emission such as productions of electricity, cement, and petrochemicals. Current CCS technologies are expensive. The IPCC panel has estimated that CCS would increase the cost of electricity by 50% or higher as well as reduces energy efficiency by 15-40%. Greater than
70% of the cost of CCS is attributed to CO₂ capture; the rest for transport and storage.

For cost reduction in carbon capture, innovations in more effective absorbent solvents, efficient solid adsorbents, high permeance and high selectivity gas separation membranes, and process design and optimization are required. Some of the world leading researchers in these fields reside in local universities and research institutes. Carbon storage, on the other hand, is a real challenge since Singapore has no suitable geological formation for sequestration. Mineralization of CO₂ by silicate minerals such as serpentine to metal carbonates and silica is thermodynamically favorable. Silicate minerals are available in abundant and sufficient quantities in neighbouring countries. It may be an option for Singapore if a cost effective process can be developed.

Development of CCS technology is hugely expensive. A cost effective approach for Singapore would be to carry out exploratory research projects, join international CCS R&D networks and participate in relevant pre-commercial demonstration projects. International collaboration should facilitate further development of any new technologies invented locally.

- **Conversion of CO₂ to fuels and chemicals**

Ideally, it makes more sense to convert carbon dioxide into useful products than storing it underground and worry about leakage. Unfortunately, conversion of highly stable carbon dioxide requires either input of energy or the presence of a high energy co-reactant such as hydrogen. Nature converts carbon dioxide to biomass by photosynthesis but with a relatively low efficiency. A worthy long-term objective would be to develop highly efficient solar-driven chemical conversions of carbon dioxide to either hydrocarbons or methanol.

Solar-powered carbon dioxide conversions may be achieved in two ways. The first involves photo-catalyzed splitting of water to form hydrogen followed by hydrogenation of carbon dioxide to methanol. Alternatively, carbon dioxide and water can be converted to carbon monoxide and hydrogen by reactions with cerium and iron oxides, respectively, at extremely high temperature (>1300°C) generated by solar concentrators. The oxidized oxides can be regenerated by thermal extrusion of oxygen and the carbon monoxide and hydrogen can be used to produce either hydrocarbons or methanol.

Both approaches have been shown to be feasible but require major scientific and technical breakthroughs in multiple disciplines to be practical. For example, the solar-powered high temperature conversion of carbon dioxide...
would require more efficient and compact solar heat concentrator, material technology to produce metal oxides that can withstand both the high temperature and phase changes due to reaction, as well as a suitable catalyst to reduce the reaction temperature. These long-term research targets would free our dependence on fossil fuels and biomass as industrial feedstock and should be supported.

3.3.2.5 Biobased polymers and composites

Polymers are the most important product of chemical industry by volume. In 2006, of the 340 million tons of basic petrochemicals produced globally, >70% went into polymers. Therefore, the polymer industry faces the same challenge for the chemical industry, i.e. the need to diversify feedstock due to rising oil price and potential cap or tax on carbon emission.

Currently, less than 2% of all polymers are derived from biomass, of which 97% are natural rubbers and cellulosics. The slow growth of new biobased polymers such as polylactic acid (PLA) and polyhydroxyalkanoate (PHA) is due to the difficulty of providing desirable properties at competitive price. Both PLA and PHA are biodegradable and PHA also possesses an excellent range of mechanical properties. However, the fermentation process to produce PHA is both expensive and emits more CO₂ than the manufacturing of polypropylene. The price of PLA is approaching those of commodity polymers; however, its growth is limited by its brittleness and low service temperature. Aliphatic polyesters based on C3 and C4 monomers are biodegradable and can possess useful properties. Some of the monomers such as succinic acid and 1,3-propanediol can be produced by fermentation of sugars. The challenge is to provide new properties at competitive cost.

It may be easier to develop biobased monomers for existing polymers. This would reduce the challenge to cost only. Prominent targets are biobased olefins derived from dehydration or condensation of biobased alcohols. A particular interesting target is to prepare caprolactam, monomer for Nylon 6, from levulinic acid derived from cellulose. The resulting Nylon 6 is not only biobased but also recyclable since Nylon 6 can be readily depolymerized to its monomer by heating. Furthermore, light weight nano clay composites of Nylon 6 with excellent mechanical properties for automotive applications can be readily prepared by reaction injection molding.

SERC research institutes possess the necessary skills required to meet the challenges in developing biobased polymers: industrial biotechnology, catalysis, and polymer synthesis at ICES; polymer physics and material science at IMRE;
polymer and composite fabrication at SIMTech; and modeling of process, properties, and structures at IHPC.

3.3.3 Assessment and stocktake of R&D capabilities needed

To successfully implement this proposed programme will require the expertise of the biology, chemistry, catalysis, computation, materials, and engineering communities in SERC as well as the wider A*STAR family. Examples of capability needs include industrial biotechnology to enhance performance of enzymes and microorganisms, advanced process analytics to detect reaction intermediates, powerful computers to model reaction mechanisms, nanotechnology to prepare nanocatalysts, advanced membrane materials for separation, microchannel reactors for process intensification, process modeling, and pilot plant design and operation.

3.3.4 Recommended timeframe

It is likely that commercially competitive alternative fossil fuel conversion technologies can be developed in the next 5 to 10 years. Most of them would be highly relevant to the existing petrochemical companies in Singapore and probably easily adaptable to existing infrastructures. On the other hand, biomass conversion technologies are likely to take longer time to develop, probably in 10 years or more. Biobased technologies could be adopted by existing multinational petrochemical companies or spawn new companies locally. For example, new technologies related to the development of new enzymes or microbes could lead to new biotech companies that specialize in either biocatalyst production or services.

3.4 Programme on Solar PV

3.4.1 Description of programme

The direct conversion of solar energy into electricity by photovoltaic (PV) cells is considered as one of the leading contenders for renewable energy source and green power production, as detrimental effects to the environment are low in comparison to the use of other energy resources. However, the cost relating to power generation is one of the several challenges the PV technology faces today. The production of Si-based PV cells is approaching 3 GW/year with billion dollars in worldwide revenue, but this figure is only representing a very small proportion of total energy generated (<1%) in the world [Ginley, 2008]. Although, silicon-based solar cells are still the dominant technology in the current market, other PV materials such as gallium arsenides and cadmium tellurides are also
penetrating into the PV market, with a desire to reduce the manufacturing cost at the same time improving the cell efficiency [Slaoui, 2007].

The development of the emerging organic and nanostructured based PV technology has attracted great interests due to its potential of low cost non-vacuum process PV technology [Shaheen, 2005]. The new organic semiconductor materials also exhibit a remarkable flexibility in turning the material properties such as molecular weight, light absorption, energy band gap for new device concept. This PV technology creates a pathway to design and synthesize new semiconductor materials that can be eventually integrated with organic-organic and nanostructure-organic composites for novel solar cells. The PV industry is experimenting with new forms of manufacturing from conventional vacuum deposition method to solution-processed techniques including printing and eventually roll to roll process. The art of organic photovoltaic ink formulation, for example, is only just being understood. For organic PV, the current efforts are centred on improving the materials properties and the device performance.

Silicon-based solar cells are proven photovoltaic technology, but suffer from relatively high costs. Organic and organic-inorganic hybrid polymer-based bulk-heterojunction solar cells offer a potentially much cheaper alternative way to harness solar energy [Günes, 2007], considerable enhancement in device efficiencies are needed if this technology is to become a viable option for large scale energy production. The development of this new PV technology is still in its early stage, particularly the design and optimization of their structure and the performance.

3.4.2 Technological opportunities and impact

A broad range of distinct device technologies, based on organic and organic/inorganic hybrid materials, are being developed very rapidly. These can include dye-sensitized nanocrystalline solar cells, polymer/fullerene blends, small molecule thin films and hybrid polymer/nanocrystal devices and nanostructured new solar cells. The main technological advances that can be expected are:

- very low-costs,
- enhanced ability to operate in dim light,
- integration of PV capabilities in building materials and fabrics, and
- ability to be printed on flexible substrates

The organic and organic/inorganic hybrid photovoltaic materials are designed for fabrication of high-efficiency solar cell belts/sheets providing affordable solar energy harvesting. The inexpensive fabrication process such as solution-process techniques, the flexibility and light weight makes this PV technology attractive for
application in new markets such as mobile electronics, disposable electronics, smart cards, digital applications, power generating windows, smart sensors, automotive, home appliances and outdoor lifestyle.

3.4.3 Existing R&D Strengths

The existing PV research in SERC aims at creating new materials, materials processes and device knowledge for organic and organic-inorganic hybrid-based photovoltaic technologies. The strategic areas of the SERC PV R&D activities are:

1. Enabling non-silicon photovoltaic materials including development of solution-processed nano-structured organic semiconducting materials with tunable optical and electric properties for optimum PV design.

2. A cheaper, more readily available and flexible PV technology that allows for high volume and scalable production processes. It is complementary to the silicon PV technology, which is the main research area that SERIS is working on.

3. Development of solar radiometry primary standards and facilities for solar cell characterization and calibration

3.4.4 Relevance and Impact to PV in Singapore

The SERC PV R&D strength in materials synthesis, materials process, device design and engineering, characterization and the calibration has enabled the acceleration of new PV technology in Singapore. Over the past three years, SERC has demonstrated its excellent capability by making significant progress in solution-processed semiconductor materials, flexible high barrier substrate systems, translucent organic PV cells, and new PV-related characterization techniques. These capabilities have also helped to attract a cluster of major PV industries, including BASF, Bosch, Bayer, Ferro Corp and Nitto Denko to collaborate with SERC RIs or to set up their R&D Centres developing future PV related technologies in Singapore.

**Materials synthesis**: strong expertise on functional and solution processable semiconductor materials for applications in light-emitting devices, thin film transistors and solar cells. The novel materials synthesized at IMRE exhibited very good quality in terms of purity and device efficiency.
Device development and integration: Some of the technologies developed on organic semiconductor materials and new device architectures for OLED/FOLED technology are already matured for commercialization. Based on the existing strengths on organic electronic device development and integration, significant progress will be made on PV technology.

Materials analysis & characterization capability: IMRE has established a wide range of sophisticated characterization and analysis tools for materials and devices. The characterization and analysis capabilities include the chemical and structural investigation, microscopy analysis and optical and electrical characterization. The characterization facilities required for PV technology, including some of the unique characterization capabilities (e.g. BEEM and PhotoCELIV), are also available within IMRE. With this wide range of facilities, IMRE is already supporting the local industry, universities including SERIS on materials characterization and analysis.

3.4.5 Proposed PV R&D Activity

In SERC RIs, the research and developmental activity on PV technology started with organic photovoltaics. The activities include the synthesis of the novel organic semiconductor materials, nanocrystals development of new characterization capabilities to study the PV materials and devices, and the development of new device architectures, fabrication process, and studying the device physics. At IMRE, in addition to the in-house projects, there are collaborative PV projects with industries, IME (under Polymer/Molecular Electronics and Devices program), local universities (NUS and NTU) on fundamental studies of PV materials and devices.

Recently, the National Metrology Centre (NMC) and IMRE have started working with SERIS with the aim to integrate SERIS strength on PV technology and SERC’s strength on Materials analysis and characterization capabilities. This will generate new projects in the near future on new characterization capabilities and manpower training which is required for the local industry as well as for the ongoing PV R&D activities. Currently, NMC/IMRE and SERIS are discussing to establish an internationally accredited lab for PV calibration and testing in Singapore. This enables the local PV industry to test their PV modules/panels within short time duration.

A*STAR RIs are working towards a SERC-wide PV Program to develop new PV technology and also train research manpower for the growing PV industry in Singapore. The aim of SERC PV Program is to build up the core competence in high performance and low-cost photovoltaic technology for application in a wide range of mobile devices where portable energy is scarce or not readily available.
The related PV research activities in SERC are complementary to the silicon PV technology SERIS has been working on.

3.4.6 Programme Roadmap and Areas to be strengthened

Although, SERC RIs have established very strong expertise in material synthesis, analysis and characterization and device development, the integration of all these efforts is still lacking. In order to make significant progress in the new PV field, an interdisciplinary approach with the international community is essential. This could be achieved through a SERC-wide PV Program (not existed currently) and through the interaction of international communities working on this field. In addition, the current PV research activity is confined within lab-scale test devices. In order to make a greater impact and progress in this field, the large area device integration capability has to be established such as inkjet printing or roll-to-roll printing. The device performance data will also need to be validated through an internationally accredited PV testing lab (e.g. U.S. National Renewable Energy Laboratory) in NMC eventually.

Nanostructured solar cells will be slightly different from current solar technology in that they will be application-driven instead of being used for utility-scale power generation. This is because the industry does not foresee nanostructured solar cells lasting 20-25 years like the panels today. More likely that they will be used for applications e.g. consumer, automobile etc. with lifespan of 5-7 years maximum.

Considering that nanostructured solar cells are likely to have shorter lifespans and used in applications other than electricity generation, we might want to have an application aspect to the research being done at A*STAR. SERC can also work with SERIS in this area since the latter has an organic solar cell component in their research (about 10% of their budget).
Figure 3.7 – SERC PV Programme – Technology Road Map

**References**

3.5 Programme on Green Buildings

3.5.1 Description of programme

Buildings and the built environment have a great impact on the environment through the entire building life cycle – be it in the initial design stage with passive design incorporated and materials selection, or at the procurement, construction, operation, maintenance and demolition stages. The main sustainability and environmental concerns lie in the area of energy and water efficiency, resource efficiency, and the amount of CO₂ emitted. These are to be balanced with social and economic concerns as well in terms of occupant health/comfort and cost efficiency.

Studies have shown that 50% of material resources taken from nature and 40% of the energy consumed in Europe are building-related, and over 50% of the national waste production comes from the building sector (Anink et al., 1996). In the U.S., it was found that 48% of all the energy consumed each year is used by buildings, and buildings are responsible for about half of the American greenhouse gas (GHG) emissions, which drive global warming. Also, more than one third of the material clogging U.S. landfills is produced by the construction and demolition of buildings (Stang and Hawthorne, 2005).

A research done by Levin, Boerstra and Ray (1995) concluded that buildings are very large contributors to environmental deterioration. According to them, buildings contribute about 15 % to 45% of the total environmental burden (See Table 3.1).

European studies also suggest that buildings are responsible for around 45% of CO₂ emissions over the ‘cradle to grave’ aspects, in addition to causing significant use of water and discharge of wastewater. (see, for instance, Working Group for Sustainable Construction 2001).

In response, global R&D efforts are being made to minimize the environmental loads, optimize energy use, reduce, reuse and recycle waste, reduce energy and water consumption, develop and apply clean and renewable energy and water resources, and improve design and maintenance practices for buildings.

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<td>Solid Waste</td>
<td>25</td>
</tr>
<tr>
<td>Land</td>
<td>12</td>
<td>Other Releases</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 3.1  Environmental burdens of buildings (Adapted from Levin et al., 1995)
The proposed Green Buildings Programme first took form with the user segment group of Building & City Managers / Developers in mind, looking at the various areas of concerns and applications in a building while keeping in view sustainability and environmental concerns and issues. The living space for this programme would be focused in the physical building structure itself, while the Eco-city Programme would cover the broader context of the infrastructure and city/district level considerations.

The Green Building programme will pay particular attention to the development of technologies that are relevant to Singapore’s context. Singapore has its unique characteristics to cater for, with its tropical climate, high-rise and high-density development and building form, highly glazed building façade for different types of buildings (e.g. commercial and residential), and its high dependency on cooling technologies. This focus will enhance the value and relevance of the programme’s research outputs for both local and international markets.

3.5.2 Programme Components

In view of all the above, the proposed Green Buildings programme broadly consists of the following:-

- Sustainable Building and Construction Materials
- Cooling and Dehumidification Technologies
- Energy Efficiency, Self-Generation/Renewable Energies
- Building Automation/Management Systems

3.5.2.1 Sustainable Building and Construction Materials

- **Advanced Materials for High Performance Building Façade**

Singapore being a tropical country near the equator is subjected to a high level of sun radiation and occasional downpours. In addition, Singapore’s planned urban developments are mostly high-rise and high-density, resulting in tall and narrow building forms and are also commonly designed with glazing façade system for aesthetics. These 2 combined characteristics give rise to cleaning and maintenance issues, glare problems, and heat reflectivity and heat transfer issues (including larger surface area with reduced internal width for heat absorption/transfer) relating to high cooling requirement and loads that affect economic payouts.

As such, there is a great demand and need for “Advanced Materials for High Performance Building Façade” with innovations like phase-change materials,
heat-reflective paints, coatings systems to reduce heat transfer (e.g. lightweight aero-gel), self-cleaning coating system (e.g. Titanium dioxide coating), and coating systems for glazing.

- Integrating greenery with buildings

Singapore has an international reputation as a tropical Garden City that is cloaked in pervasive and verdant greenery. Such a reputation has given Singapore a unique image and a competitive advantage, and the pervasiveness of greenery has softened the otherwise harsh “concrete” environment, and provided numerous environmental benefits such as the mitigation of the urban heat island effect, air pollution and stormwater discharge. As land use development in Singapore continues to go highrise and high density, a useful strategy to pursue is the concept of plants functioning as an intelligent “living skin” for buildings facades. Akin to natural cooling and physiological processes in plants that control air and moisture exchange through the leaves, a living skin for buildings can regulate thermal exchanges between the indoor and outdoor environment and regulate indoor environment quality (IEQ) through removal of pollutants and regulation of humidity in indoor environment. The use of a green living skin can also enhance the image of the building, enhance contact with nature to improve occupant well-being, health and comfort, all of which have been shown to increase work productivity.

Research on living skin will seek to optimize the regulatory processes in plants to function as an intelligent façade. Other research areas will also include new or hybrid species of aesthetically pleasing plants that are low maintenance (robust, needs little water, slow growing); plants that harness solar radiation and converting it to useful forms for building use – all without affecting the building integrity yet whilst enhancing occupant comfort and well-being; and lightweight structure for roof planter boxes and vertical greenery systems (including soil) – weight and maintenance issues especially with regards to high-rise, high density buildings in Singapore and other countries like Hong Kong.

- Cost-Effective Alternatives to Basic Materials

In addition, with massive construction activities going on in countries like China, Dubai and India, be it for land reclamation or for the construction of a building, basic materials like sand and aggregates are essential and cost-effective alternatives have to be created or sourced to reduce our dependency on such limited/exhaustive basic materials. This reduces the
influence of market price fluctuations/volatility (rapid construction price increase in the past 2 to 3 years) and resource availability (e.g. Indonesian sand ban in 2007) on our construction processes and deadlines.

Innovations of cost-effective alternatives to basic materials that are at the same time sustainable, include the idea of turning waste into useful construction materials (e.g. turning demolition waste to concrete – recycled concrete aggregates (RCA), replacement of cement with incineration ash or fly ash). A study done in Sweden showed that the environmental impacts of reused materials corresponded to about 55% of the impact that would have been caused if all materials had been new (Thomark 2000). Another study showed that 12 to 40% of the total energy used for material production could be saved by using recycled materials, indicating considerable potential energy savings through the reuse of materials. This makes our construction processes more cost-effective and sustainable, with less impact on the environment in terms of the use of natural resources, waste disposal and pollution control.

3.5.2.2 Cooling and Dehumidification Technologies

Singapore, similar to many other tropical countries, faces the issue of having high ambient temperature and humidity levels. Such weather conditions as well as human activities within the building require our highly enclosed structures to be greatly dependent on cooling and dehumidification. The challenge to provide comfortable indoor environment and air quality is further heightened as Singapore’s planned urban developments are mostly high-rise and high-density, resulting in tall and narrow building forms. Our buildings are also commonly designed with glazing façade system for aesthetics. This gives rise to problems like heat reflectivity and heat transfer within the building including a larger surface area with reduced internal width for heat absorption/transfer.

Human activities like the use of computers, copier machines, and human movement also result in heat production. For the computers and machines that support human activities to function efficiently and last longer, moisture has to be controlled as well. Thus, it is important to have cooling and dehumidification within a building, given its impact on the activities within the building, the occupant’s health, comfort level, and productivity. This also has high relevance to reducing Sick Building Syndrome. Most importantly, the energy requirements and economic costs (capital, maintenance and replacement costs as well as daily consumption) involved are usually the greatest compared to other building systems like lighting or vertical transportation requirements.

Modeling and simulation for cooling and dehumidification process is also one of the important aspects that this green building program can capitalize on it. The
multi-physics transport phenomena involved in this cooling and humidification technologies such as condensation water vapour, material expansion and shrinkage as well as the macroscopic effect on human comfort can be simulated with certain level of accuracy. The core research capabilities available within SERC’s Institute of High Performance Computing (IHPC) include computer simulation for electronic thermal management, green data centre, testing the performance of the technologies, as well as for solving the heat transfer issues in building design and manufacturing process.

Thus, there is a need to place attention in the area of cooling and dehumidification technologies. Possible areas of research include thermally activated cooling and dehumidification technologies including absorption and adsorption refrigeration, and solid and liquid desiccant systems.

3.5.2.3 Energy Efficiency, Self-Generation/Renewable Energies

Most, if not all, of the activities within a building require electrical energy. Electricity is required to power the air-conditioning, computers, machines, lighting, tele-communication services, and even the hot water dispenser. The International Energy Agency (IEA 2005) estimates that buildings account for 30-40% of the worldwide energy use, which is equivalent to 2,500 Mtoe (million tons of oil equivalent) every year.

- **Energy Efficiency**

  Thus, there is an immense need to place focus as well on the area of energy efficiency. If energy usage (example, for lighting systems within a building), can be reduced due to having a more energy efficient technology/system, it will not only be a step to creating a more sustainable building and environment but also help reduce the economic burden to pay for the energy consumption within the building. Energy efficiency and cost efficiency can be balanced with each other, as well as with sustainability and environmental concerns such as “carbon footprint”.

  For example, motion sensors are now often included for lighting systems and escalators. During off-peak hours, lights or escalators, which are originally in a sleep mode, will be activated only when human motion is detected. This not only helps to reduce energy consumption and operational costs, but also prolongs the life span of the lightings with reduced usage (leading to increase cost efficiency in the long run).

  In addition to the above, daylighting solutions and technologies can be further enhanced to reduce dependency on mechanical lighting within a building,
thus reducing energy usage and creating greater economical sense while making full use of Singapore’s abundance of diffused lighting, a natural resource. Studies on benefits of daylighting solutions have shown that natural lighting makes the occupants feel healthier and in turn improves the occupants’ work efficiency and productivity.

Other ways of effecting energy efficiency, related to cooling technologies, include personalized cooling in buildings and even homes. The concept of this is to cool the space users themselves, instead of reducing the temperature of the entire space of each room. Such technologies can range from innovative ways to channel or direct cool air to the person sitting in an office cubicle, persons in a meeting room, person sitting in front of a television at a study table or lying on the bed, to air-conditioned personalized suits. This can significantly reduce energy usage. There has been research done in this area in the past years and it can be further looked upon especially with the great potential of energy usage reductions and savings of this technology.

- **Building Integrated Renewable Energy**

  Research efforts in the area of renewable energy sources for buildings are also important. This has been on-going since more than a decade ago overseas and within the last few years in Singapore. In Singapore’s context, solar energy offers the most potential in building-based renewable power generation, as we can tap on relatively high levels of solar radiation throughout the year.

  Besides improving energy efficiency, buildings can reduce energy consumption from outside sources and its carbon footprint by self-generating renewable energy within the building itself, for example through Building Integrated Photovoltaic (BIPV) technologies. The building can then self-generate energy for its consumption and reduced its reliance on the centralized power grid.

  It is important for the development of a green building to adopt an integrated design approach from the initial phase, so that it would be able to incorporate design specifications, building codes and technology. Energy requirement can be reduced significantly through energy efficient design and renewable energy sources such as rooftop solar panels can complement energy needs. A report by Alliance to Save Energy to develop a Zero Energy Building showed that 80% of requirements could be met through load reduction while the remaining to be achieved through use of renewable energy.

3.5.2.4 **Building Automation/Management Systems**
In line with the abovementioned on energy efficiency, another area to make buildings sustainable holistically is to further research efforts on the Building Automation/Management System (BAS/BMS), for example in the creation of a software and/or integrated control, monitoring, problem detection and solution-providing system. The BAS or BMS is used by the facilities managers of a building and sometimes the building occupants to control and manage their usage of the various components/systems of a building – the air-conditioning, vertical transportation, lightings, etc – and thus the usage of energy (and water) in the building.

With a more reliable and integrated system, building users and facility managers can better monitor the activities within the building, pre-empt possible situations and problems and provide more effective and efficient (fast, economical, reduced energy consumption) solutions and actions. This has benefits in creating a safer, more adaptable, yet stable, integrated functioning of a building and its activities. Occupants can also enhance the ease of performing their work activities, efficiency, and productivity level. For example, if a group of building users need to work overtime for a night, they can apply for it online through an integrated system connected to the BAS/BMS and the automated system would compile requests, allocate the area at which the air-conditioning and other systems are switched on (floor area and its related systems are sectioned), send out confirmation emails, as well as control/monitor usage and comfort level with thermostats. In addition to the above, facilities managers can also track usage and reduce energy consumption with the BAS/BMS which keeps energy consumption data, track and identify trends and propose possible energy reduction solutions.

3.5.3 Economic and Technological Opportunities and Impact

In section 3.5.1, the impact that buildings and its processes and usage have on the environment has been highlighted. Much material, energy and water resources are consumed by buildings. Even a great extent of waste production and emissions into the environment has its origins related to buildings. As such, there is great opportunity involved in branching into ways to reduce the “building footprint” on the environment.

There are many components in a building – the basic materials used, the end-product applied in the building, the composition of various items to form a building system – and various stages in a building’s lifecycle – design, procurement, construction, operation, maintenance, refurbishment, demolition. As such, there comes about many ways/angles to look at a building and identify
means or areas at which work can be done to enhance sustainable development and environmental impact.

With the increasing awareness of environmental impacts and the need to act on it, as well as corporate social responsibility, building developers, managers and end-users are increasing responsive to environmental concerns. It has been exemplified in Singapore’s Green Mark Scheme for buildings, where there has been an increasing trend for developers to “green” their buildings. This is trend even with the current economic downturn. Some end-users, for example residential unit owners, also look out for whether their private residential development has the Green Mark label, and at which level of Green Mark, to certify its promise and extent of sustainability and “green-ness”. In a market survey conducted by BCI Asia, more than half of the companies surveyed (51%) felt that despite the upfront costs, green buildings would help promote sales, in terms of occupancy and rent ratio, and improve profit margins. In terms of specific interests from the firm’s perspective, the table below summaries the top 3 features that companies would like to see now and in the future.

Features of Green Buildings which companies considered most important:

<table>
<thead>
<tr>
<th>Rank</th>
<th>Present</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heating and lighting monitoring systems</td>
<td>High efficiency HVAC systems</td>
</tr>
<tr>
<td>2</td>
<td>High efficiency HVAC systems</td>
<td>Heating and lighting monitoring systems</td>
</tr>
<tr>
<td>3</td>
<td>Reflective roofing materials</td>
<td>Lifecycle consideration of materials used</td>
</tr>
</tbody>
</table>

There are also cases of overseas applications for Green Mark audits to be done in their buildings as well. Some countries, like Malaysia, have also started formulating their green standards. This shows the increasing awareness and receptiveness of people in our nearby region to sustainability concerns in a building. It would reap benefits if we could export our knowledge and end-products. The exportability of standards is also evident in China, where several developments such as the Olympic Village and Century Prosper Centre in Beijing have achieved the U.S. Leadership in Energy and Environmental Design (LEED) Gold certification.

The building lifespan spreads more than a decade or two. Thus, decisions made and actions done in the course of the building lifecycle makes a great difference. The economic returns especially, with regards to a higher efficient air-conditioning system, can be substantial in the long run.
It must be highlighted as well, according to the cost and energy data collected from projects with the Green Mark label in 2008, the capital cost for greening a building takes about 1 to 4% of the total construction cost, with payback years ranging from 2 to 7 years. This does not take into account the tangible and intangible benefits in the long run like lower energy consumption, and thus lower electricity and water bills, and improved occupant health, comfort and productivity. All these easily outweigh the initial green cost incurred and not all green features are definitely more expensive.

Besides strengthening our existing local capabilities in green building solutions, there is also a strong commitment to develop and enhance Singapore’s role as a “living laboratory” for sustainable and clean urban technologies and solutions - where new concepts and prototypes are developed at research centres and universities in collaboration with private sector partners, applied quickly through strongly-supported first adoption and testbedding programs, and further developed, exported and commercialized to serve global markets. By leveraging on Singapore as a reference site for testbedding new solutions, we are expanding the variety and sophistication of solutions that we can deliver.

Thus, there is much economical and technological opportunities and impact for/of green buildings – the research work and its spin-offs, in terms of the processes, by-products, applications, and the tangible and intangible benefits to be reaped. There is potential to “green” the existing sectors as well as create new industry sub-sectors focusing on green/sustainable and integrated options. The increased awareness and receptiveness to sustainability and green buildings will also allow for possibilities to leverage on new or existing developments by large or small industry players to validate and testbed/demonstrate the new technologies.

Also, as highlighted earlier, by taking a holistic and integrated approach in promoting green building, Singapore can provide and/or develop thought leadership in design, modeling and system integration through designers, architects, consultants, property developers, technology suppliers, and academic institutions.

It is therefore natural for A*STAR to leverage on this strong foundation, and work with other agencies and industrial partners to support R&D in this area through the Green Buildings research program.

In order to support further economic growth and needs of our future population, Singapore will continue to develop and more buildings will be needed. Therefore, there is a high demand and need for sustainable building solutions. We have a competitive advantage of being more technologically improved compared to most of the countries in the Asia-Pacific region. We are able to leverage on current research capabilities, applied technical capabilities and experience of the local
industry players to enhance our current technologies, keep up with everyday technological progressions and be on comparable levels with the European/American building and construction industry. Being one of the forefront countries in this area within the Asia-Pacific region would also allow us to export our expertise and knowledge to other countries, reaping tangible and intangible social and economic recognitions and returns.

### 3.5.4 Assessment and Stocktake of R&D Capabilities Needed

There are existing capabilities available or being developed by research institutions and local universities like NUS, NTU and A*STAR. Other bodies supporting environment or building-related research in the form of research funding are for example, NRF, A*STAR, IHLS, MND, BCA, MEWR and NEA. The following lists the existing R&D programmes and initiatives that may include building-related research work:-

1. National Research Foundation (NRF)
   - Strategic Research Programme on Environment & Water Technologies (includes clean energy)
2. A*STAR
   - Energy Technology R&D Programme
   - Other initiatives / projects under RIs, PSF, TSRP
3. Institutes of Higher Learning (IHLs)
   - NUS – NERI, SERIS, CTBP, ESU, etc
   - NTU – NEWRI
   - Polytechnics – various smaller centres and initiatives in environment, water and clean energy
4. MND/BCA
   - Research Fund for the Built Environment, including Zero Energy Building, eco-city interest, etc
5. MEWR/NEA
   - Innovation for Environment Sustainability Fund
6. Clean Energy Research Programme, SERIS

There has been an increasing trend to move research work from being purely academic to have more applied technologies and to include partnering with industry players so as to bridge the gap for easier applications in the actual construction of a building. This is especially relevant for sustainable and green building technologies and research work, and which could be further developed upon.

In relevance to moving research work towards being more easily adopted and applied in the building and construction industry, there arises the need to incorporate and/or integrate the idea and aspect of cost and adoptability. There is
no doubt that cost and the convenience to obtain the technology and apply it in the building are the two main concerns of the various parties involved. As such, it is important to always think of making the research/technologies cost-effective and easily attainable and applied.

New capabilities can also be developed in the area of training and creating “green” jobs, which the Singapore government has been advocating in the recent Budget release, as well as in the enhancement of the synergy and interaction between the various research institutions and projects for a more well-rounded research platform and environment in Singapore and its nearby region.

In countries like America, there have been much support for, effort put in and research work done in the area of sustainable development and green buildings, including sustainable construction. For example, there is the U.S. Green Building Council (USGBC), a non-profit organization that is dedicated to expanding green building practices and education, and has a Green Building Research Fund created to spur green building research that will advance sustainable building practices and encourage market transformation.

In the Asia-Pacific region however, especially in the Southeast Asian countries, “green” capabilities are limited and Singapore has the competitive advantage being one of the forefront runners doing green building research work, especially in relation to our unique characteristics and climate conditions.

3.5.5 Recommended Programme Roadmap and Milestones

The Green Buildings programme aims at a medium term time frame of approximately 5 years.

It is proposed that research efforts be placed in the following areas:-
  a. Sustainable Building and Construction Materials
  b. Cooling and Dehumidification Technologies
  c. Energy Efficiency, Self-Generation/Renewable Energies
  d. Building Automation/Management Systems

Prioritization may be required as it may not be possible to embark on all the 4 areas concurrently. We have to look beyond the current economic outlook, as well as place some focus on the existing building stock as it takes up a greater percentage of the buildings in Singapore or in any other countries and energy efficiency and reduced consumption for these existing buildings is essential.

It is therefore recommended to place emphasis on solutions that reap benefits not only for new developments but also for the existing building stock especially in the area of energy efficiency, namely, energy efficient technologies and
design, and building automation and management system. Not overlooking the fact that a large portion of a building’s energy load and bills is a consequence of the cooling and dehumidification system, this area should be placed on high priority under research efforts for energy efficient technologies and design.

However, this does not mean a standstill for research efforts in the other areas as they are still very important when holistically aiming at reducing the environmental impacts of buildings and the related repercussions (e.g. carbon footprint) and they still do play an important role in the path of sustainability.

References


3.6 Programme on Energy Storage

3.6.1 Introduction

The focus of this programme is on electrical energy storage, primarily through the use of secondary (rechargeable) batteries and super/ultra capacitors. These are the storage technologies that offer the most potential for Singapore and A*STAR to be competitive in research and development efforts, as compared to alternative storage technologies involving flywheel, pumped (water), compressed air, and thermal energy storage technologies.

Energy can be distributed and utilized in many different forms (including mechanical, chemical, electrical and thermal), and provides a variety of different energy services such as lighting, heating, cooling, computation, communication, mechanical/drive power, and transport.

However, electricity is the preferred form of distributing and utilizing energy in modern economies because it is clean, flexible, and relatively easy and efficient to distribute over long distances. Electricity is also the form of energy that is most compatible with an increasing digital and knowledge-based world. However, compared to other forms of energy, e.g. chemical energy in liquid fuels, it is difficult to store electricity in a cost-effective, safe, efficient, compact and environmentally friendly way.

In spite of these challenges, it is clear that the existing and potential applications of electrical energy storage are many and wide, and can potentially contribute to energy efficiency in power and energy systems, and the wider use of clean and sustainable energy, thereby contributing to sustainable development.

3.6.2 Economic and technological opportunities and impact

A battery is much more than a power source - it is an enabler of new applications that will drive technologies and markets. Without improvements in rechargeable battery technologies, the mobile phone as we know it would not have been a possibility, even with the miniaturisation of electronics. It would be bulky and heavy, much like a brick and also would not allow much more than 30 minutes of talktime. With the advent of modern battery technologies, we have today massive telecommunication companies, content providers, handset makers and the iPhone - an entire industry grown around a single device.

18 For example, electrical power constitutes about 30% of energy use in less developed economies, but close to 50% of energy use in developed economies such as Singapore and Western Europe.
Electrical energy storage has the potential to be an enabler of new and exciting applications that will drive technologies and markets. For example, they are critically important in the following applications:

- Portable, personal, and hand-held consumer devices and tools such as calculators, mobile phones and PDAs and digital cameras where storage enhances the usefulness and functionality of these devices and tools to increasingly demanding users

- Power system/grid applications such as uninterruptible power supply (UPS), demand-supply matching, and load leveling/peak shaving, and facilitates the wider use of intermittent and less-despatchable renewable and distributed energy technologies such as solar, wind, and cogeneration systems.\(^{19}\)

- Electric transport systems and vehicles (for example, as part of starting system in conventional vehicles, and more importantly, providing traction power in various types of electric vehicles, ranging from hybrid, plug-in hybrid, pure electric, and in the longer term, fuel cell electric vehicles. Electric vehicles offer opportunities to diversify use of energy resources, enhance energy security, improve energy efficiency and de-carbonise the transport sector.

\(^{19}\) There is therefore potential overlap in technology areas with other programs and areas under the Sustainable Development theme, such as Smartgrids and Urban transport research areas under the “Intelligent eco-city infrastructure and systems” program.
The total market for rechargeable batteries is set to grow 13% year-on-year from over US$40 billion in 2008 to over US$70 billion in 2016. Of this market, smaller scale applications, such as portable devices and small-scale UPS, are fairly mature although technological improvements are still being made. However, in the near to medium term, it is in the “larger format” applications, such as power grids and electric vehicles, where cost reduction and technical innovations and improvements offer the most attractive growth and rewards. The higher power lithium ion market alone, serving power tools, outdoor power equipment, grid storage and HEV/EVs, is projected to grow 131% on year to reach US$16 billion by 2016. Almost all major car manufacturers are now pursuing aggressive time-frames to roll-out different types of electric vehicles.

Figure 3.9 shows the large variations in electrical power load demand, and illustrates the potentially critical and transformational role of energy storage in reduce cost and increasing efficiency, for example, through reduced and delayed investments in generation capacity and power transmission and distribution.

Figure 3.10 compares the **power density** (W/kg) and **energy density** (Wh/kg) for batteries, capacitors, fuel cells and the internal combustion engine, while Figure 3.11 compares the power and energy characteristics of different battery technologies. Figure 3.11 indicates the superior performance of advanced battery technologies such as Lithium-ion batteries. Such batteries are currently the focus on many battery R&D groups both in academia and industry, with cost reduction and safety enhancement being key research challenges.
Figure 3.9 – Typical electrical power profile\textsuperscript{20}

![Typical Electrical Power Profile]

Figure 3.10 - Overview of different battery technologies in terms of specific power and specific energy\textsuperscript{21}


Research challenges for electrical energy storage technologies are manifold, and include enhancing mechanical and chemical stability, improving abuse tolerance, improving cycle life and durability; improving storage and power capacities/densities; extending temperature range of operation; improving discharge and charging characteristics and control; reducing costs; and enhancing safety.

The following areas of research are proposed to meet these challenges:

- Materials and cell level research
  - New multi-purpose and nano-materials for batteries and supercapacitors
  - Advanced modelling of materials and fundamental processes and mechanisms
- Device level research
  - Optimization of Battery/supercapacitor design and optimization through advanced modelling and analysis

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• Thermal management to ensure safety, efficiency, durability
  • Systems level research
    o Application-specific system optimisation and integration – e.g. power electronic interfaces and battery management systems to charge, discharge, and manage storage systems in battery systems for electric or plug-in hybrid vehicles
  • Manufacturing level research
    o Cost-competitive, environmental friendly and sustainable manufacturing, and recycling/disposal (end-of-life) technologies and systems

3.6.3 Assessment and stocktake of R&D capabilities needed

These research challenges have to be addressed using a wide-array of research capabilities and innovations in areas such as electrochemistry, advanced materials (including nano-materials and nano-structures), sustainable design and manufacturing, advanced control, automation and thermal management.

Existing capabilities in Singapore include

  • Basic research level
    o Materials and nanotechnology (IMRE, NUS, NTU);
    o Modeling/analysis – electrochemical, thermal etc. (IHPC, NUS, NTU)

  • Systems/ Applications level
    o Integration and application of batteries in intelligent grids, microgrids, and in Green data centres, UPS systems, hybrid renewable energy systems, EVs, (NUS, NTU, including through IEDS program, EPGC)

  • Manufacturing level research
    o Manufacturing automation and sustainable manufacturing technologies (SIMTech)

3.6.4 Recommended programme roadmap and milestones

System, applications, and manufacturing level research require short to medium time-frames, of up to five years. Existing capabilities and activities would already provide important headstart, for example through the development of Experimental Power Grid Centre (EPGC)’s microgrid research facility.
Basic research would take a longer time frame, but inherent strengths in advanced materials (including nanotechnology) would enable research capabilities to be applied to the more basic research areas of this programme. Ultimately, effort should be made to develop application-sized prototypes that validate the lab-scale cells and devices that will be initially developed.

3.6.5 Bibliography


3.7 Research Programme on Intelligent Eco-city Infrastructure & Systems

3.7.1 Introduction

Over the last few decades, rapid economic development across the world has been accompanied by significant increases in urban population. In 2007, the number of people living in urban areas exceeded those in the rural regions for the first time. Asia’s cities are currently home to 1.6 billion people, but the U.N. expects that number to rise by another 1.8 billion people by 2050. China - which is now 40 per cent urban - will have 1 billion people (70 percent) living in urban areas by then. Globally, the UN’s projection of the trend over the next 20 years is shown in Figure 3.12 below.

Figure 3.12 - Projected World Rural and Urban Population, 1950-2030

“Cities are increasingly becoming the engines of national economic growth and the magnets for new residents flooding in from rural areas. Globalisation is having a significant effect on cities, forcing them to compete for international business with other cities worldwide and within their own countries. …

As a result, the sustainability of cities is under pressure. Decision-makers at all levels are faced with the task of how to resolve urban problems from

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23 Source: UN report, UN Population Division of the Department of Economic and Social Affairs (DESA), 2008.
transportation to waste management, from drinking water supply to the preservation of urban green space”.

This programme will address the pressing need to develop and commercialize new technologies that would enhance the sustainability of cities, focusing on technologies to create “intelligent” systems to serve eco-cities. These technologies will optimize the use of limited and depleting resources, reduce the environmental impacts and eco-footprint of the buildings, facilities, transport systems and other infrastructure that serve the eco-cities, while maintaining the social and economic vibrancy and activities of such cities. They will have to interface with both new and legacy systems and build capabilities to integrate these systems into city-scale solutions.

Three sub-programmes have been identified based on the criteria of high market need, relevance to Singapore, as well as global trends that point to the high potential for technology and innovation to be applied to serve these needs. The sub-programmes are:

- Next generation smart grids
- Urban transport systems
- Eco-city management.

3.7.2 Economic and technological opportunities and impact

Over the years, Singapore has amassed considerable expertise in urban planning, land use, housing, transport, clean air and water management, and has already proven itself to be a “model city” in terms of sustainable development. The UN HABITAT’s State of the Worlds’ Cities Report 2008/09 cited the city-state as an example of good governance and balanced development. Singapore was the only city surveyed without slums, and scored well on comparative rankings in areas such as pollution levels, energy consumption, public housing and car ownership.

In recent years, there is also a strong commitment to develop and enhance Singapore’s role as a “living laboratory” for sustainable and clean urban technologies and solutions - where new concepts and prototypes are developed at research centres and universities in collaboration with private sector partners, applied quickly through strongly-supported first adoption and testbedding programs, and further developed, commercialized, and exported to serve global markets. (See Figure 3.13)

It is therefore important for A*STAR to leverage on this strong foundation, and work with other government agencies and industry partners to undertake R&D in this area.

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24 Source: http://www.rec.org/REC/Programs/SustainableCities/Problems.html
3.7.3 Description of programme

For this program, the focus is on developing technologies for “intelligent” eco-city infrastructure and systems, including smart grids, urban transportation, and the management of eco-cities. Possible innovations and technologies to be developed under this program are outlined below, and will complement those being considered for other research programs proposed under the Sustainable Development theme that also contribute directly to technologies for eco-cities - such as Waste Management and Green Buildings.

The innovations and technologies developed will contribute to energy and resource conservation, management and optimization; reduction, recycling and management of waste; reduction of (global) greenhouse gas emissions and (local) pollutants (resulting in better health and well-being); and support the diversification of energy and material resources to promote sustainability and security.

Source: EDB (Urban Solutions group)
3.7.3.1 Next generation Smart grids

The reliable, efficient and cost-competitive production and delivery of electrical power is crucial to economic growth and activities in cities, especially in digital, knowledge-based economies. However, it is generally recognized in many countries that the power infrastructure is due for a major overhaul after decades of relative neglect, under-investment, and relatively low levels of technological innovations. These systems were implemented in an era where primary energy was relatively inexpensive.

Grid reliability was ensured by having excess capacity in the system, with a unidirectional flow of electricity from centrally dispatched power plants to end-users. It followed that infrastructure investments were channelled towards further increasing this capacity in order to cope with growing demand, instead of modernizing or transforming the electricity network. This lack of investment, coupled with utilities' cost-recovery models that depreciate assets over 30-40 year timeframes, has led to an increasingly inefficient and unstable grid system in many countries.

The International Energy Agency has estimated that the electricity sector (comprising power generation, transmission and distribution, and excluding end-use technologies such as lighting, air-conditioning and heating) will require almost $10 trillion over the period from 2001-2030, or 60%, of total energy investment. (See Figure 3.14)

![Figure 3.14 - World Electricity sector investment outlook](image)

Figure 3.14 - World Electricity sector investment outlook

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26 Source: World Electricity sector investment outlook, IEA, 2003
An important approach to overhauling and advancing the power infrastructure is through the use of “smart grids”, and technologies associated with them are receiving considerable attention from governments and companies all over the world.

The key features of smart grids as compared to today’s grid are outlined in Figure 3.15.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Today's Grid</th>
<th>Smart Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enables active participation by consumers</td>
<td>Consumers are uninformed and non-participative with power system</td>
<td>Informed, involved, and active consumers - demand response and distributed energy resources.</td>
</tr>
<tr>
<td>Accommodates all generation and storage options</td>
<td>Dominated by central generation - many obstacles exist for distributed energy resources interconnection</td>
<td>Many distributed energy resources with plug-and-play convenience focus on renewables</td>
</tr>
<tr>
<td>Enables new products, services and markets</td>
<td>Limited wholesale markets, not well integrated - limited opportunities for consumers</td>
<td>Integrated wholesale markets, growth of new electricity markets for consumers</td>
</tr>
<tr>
<td>Provides power quality for the digital economy</td>
<td>Focus on outages - slow response to power quality issues</td>
<td>Power quality is a priority with a variety of quality/price options - rapid resolution of issues</td>
</tr>
<tr>
<td>Optimizes assets &amp; operates efficiently</td>
<td>Little integration of operational data with asset management - business process silos</td>
<td>Greatly expanded data acquisition of grid parameters - focus on prevention, minimizing impact to consumers</td>
</tr>
<tr>
<td>Anticipates and responds to system disturbances (self-heals)</td>
<td>Responds to prevent further damage - focus is on protecting assets following fault</td>
<td>Automatically detects and responds to problems - focus on prevention, minimizing impact to consumer</td>
</tr>
<tr>
<td>Operates resiliently against attack and natural disaster</td>
<td>Vulnerable to malicious acts of terror and natural disasters</td>
<td>Resilient to attack and natural disasters with rapid restoration capabilities</td>
</tr>
</tbody>
</table>

Figure 3.15 – Features of the smart grid

Smart grid technologies would fall into one of the following two broad categories:

<table>
<thead>
<tr>
<th>Category</th>
<th>Types of Devices / Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart Grid</td>
<td>• Integration of renewables</td>
</tr>
<tr>
<td>Applications</td>
<td>• Grid monitoring and management</td>
</tr>
<tr>
<td></td>
<td>• Smart metering</td>
</tr>
</tbody>
</table>

Smart grid technologies offer the potential to significantly reduce costs, whilst enhancing efficiency, safety, reliability, security and quality of power production and delivery. They will provide the critical integration between energy/power supply and end-use/demand that is currently lacking in the power sector.

Smart grid research, development and demonstration are currently receiving very high levels of interest from both governments and industry. Both the EU and US have substantial programs related to smart grids, and this has been reinforced recently in the US with announcements of multi-billion dollar funding under the *American Recovery and Reinvestment Act of 2009*, that are targeted specifically for investments, demonstrations and R&D in smart grids.

Technologies of interest under this research programme include:
- advanced meters and sensors,
- power electronic interconnection technologies,
- applications of energy storage, and
- advanced energy/power control and management technologies
- secure, low-cost communications technologies that enable interoperability

These technologies will enable matching and integration of supply and demand, including the wider use of renewable and distributed energy resources that often pose challenges in terms of intermittency and dispatchability.

Morgan Stanley estimates that the smart grid technologies market will grow from US$20B in 2009 to US$100B by 2030, with a CAGR of 9%. Despite the upside potential this market presents, the most growth will only be achieved in areas where IT companies (e.g. Cisco and IBM) can establish partnerships with utilities and regulatory bodies to jointly develop smart grid platforms and regulatory frameworks.

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28 For example, the EU has a substantial program to develop Europe’s electricity networks of the future under the SmartGrids Technology Platform, Directorate-General for Research Cooperation (Energy)
29 The Energy Independence and Security Act of 2008 already contained substantive references to smart grids under Title XIII
30 A separate program on Energy Storage is also proposed
Given the complexity involved in growing this industry sector, it is plausible that the pro-business environment in Singapore could prove to be a strong value proposition in the following areas: (i) Quick development of new IT-based grid platforms which can be test-bedded on selected households in Singapore; (ii) The devising of regulatory frameworks and mechanisms which can also be test-bedded on selected communities within Singapore to monitor and record consumer responses and behaviour.

Companies could collaborate closely with the Energy Market Authority\(^{31}\) to achieve the above outcomes, and as more of such outcomes result from successful experimentation here, Singapore would provide added leverage as a working showcase for them and eventually, as a launch pad for global export.

### 3.7.3.2 Urban Transport Systems

Land transportation infrastructure and systems for the efficient movement of people and goods are critical to eco-cities. Energy-efficient (rail and bus) public transport networks are preferred solutions for movement of people within urban centres, but road-based transport in the form of passenger cars and goods trucks are also important to provide the required mobility function and quality of life for urban dwellers. At present, there are roughly a billion motor vehicles in the world, and this is expected to double within twenty years, largely a consequence of explosive growth in China and India (see Figure 3.16).

Due to land space constraints and to enhance efficiency and reduce carbon emissions, Singapore’s land transport policy is focused on making the use of public transport a “choice option”. Nevertheless, the government recognizes the aspiration of citizens to own and use cars, and have continued to allow controlled growth of vehicle population, and commit investments to road and highway expansion.

\(^{31}\) These agencies have recently formed a Intelligent Urban Energy Systems task force to coordinate efforts and implement action plans to make Singapore’s energy and power system more “intelligent”.


Intelligent transport

In order to manage congestion and optimize the use of our transportation infrastructure, LTA sees potential collaboration with industry and other partners in the following areas related to “intelligent transport”:

<table>
<thead>
<tr>
<th>Focus area</th>
<th>Short-medium term (1-3 years)</th>
<th>Medium-long term (3-5 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road optimization</td>
<td>Travel pattern analysis</td>
<td>Traffic sensors &amp; robotics</td>
</tr>
<tr>
<td></td>
<td>Real time traffic controlled public transport priority system</td>
<td>Open source road traffic simulator</td>
</tr>
<tr>
<td></td>
<td>Alternative traffic monitoring technology</td>
<td>Predictive traffic monitoring</td>
</tr>
<tr>
<td>Congestion management</td>
<td>Taxi, bus on-demand supply &amp; demand management</td>
<td>Automated road vehicle</td>
</tr>
</tbody>
</table>

Another area of strong interest in Urban Transportation is clean transportation. There are a multitude of alternative (to fossil fuel) propulsion technologies today: biodiesel, CNG, LNG, fuel cell, electric and hybrids. Each technology proposes to have lower carbon emissions. Most of these technologies are already past the prototype stage and are getting ready for full commercial production. Some countries have come up strongly to favour one technology over the other, e.g. Iran with CNG, Israel with electric vehicles. There seems to be a consensus that while fuel cell vehicles can potentially be fully zero emission, it will be at least 10-20 years before they will reach full-scale commercialization because of high vehicle cost and challenges in setting up hydrogen infrastructure.

Momentum for Plug-in-Electric Vehicles (PHEV) or Full Electric Vehicles (FEVs) has picked up significantly in the last year, driven by high oil prices and environmental concerns. Major car OEMs like Renault-Nissan, Mitsubishi, Daimler, BMW etc have started EV programs, with large scale commercial production starting in 2009/2010 and first vehicles rolling out 2010/11. Many
countries like Israel, Australia, Hawaii, Japan, Hong Kong have all signed up to EV-pilot/adoption programs.

OEMs have remarked that Singapore is an ideal place for EV adoption, given our small geography and strong grid infrastructure. Preliminary calculations indicate potentially around S$70M of saving per year to consumers if 10% of our car population become electric, and cost parity with conventional vehicles potentially being reached between 2015-2017. In addition, savings in carbon emissions and energy consumption will also be realized. Nevertheless, these numbers will need to be validated through a real life EV testbed.

A multi-agency Electric Vehicle Task Force has been formed, and initiatives to encourage testbedding and developing of necessary infrastructure for electric vehicles have been introduced in collaboration with industry partners.

An overview of the characteristics of different electric vehicle technologies is provided in Figure 3.17. The environmental and efficiency benefits of such vehicles, especially if charged through low-carbon power generation technologies (such as nuclear and renewable energy) offers a compelling case for their use in a small city-state like Singapore.

Examples of research areas for clean vehicle technologies include:

- Low-environmental footprint, high-value and high-technology materials and components for new clean and efficient vehicle technologies\(^{33}\) (including lightweight/durable materials, vehicle electronics, power electronics, fuel cells and batteries\(^{34}\) for electric vehicles and personal transporters with reduced environmental impacts)
- Infrastructure to support electric and other clean and alternative fuel vehicles, such as fueling infrastructure for biofuels, battery charging or replacement stations for EVs

\(^{33}\) Research in alternative transport fuels such as biofuels and hydrogen are proposed to be carried out in another program (on Sustainable Fuels, Chemicals & Materials) under the Sustainable Development theme.

\(^{34}\) A separate Energy Storage research program under the Sustainable Development theme is also proposed to serve both energy and transport application needs
Figure 3.17 - Overview of the electrification paths for advanced vehicle technologies

Electric vehicles offer Singapore a chance at another bite at the automotive cherry. EVs will bring about a new automotive supply chain for components such as battery, power electronics, as well as new materials. Short term industry growth forecasts EV production volumes of about 1.8 million units in 2011. However, the future car industry in 2050 is estimated at 2 billion units, so even if EVs take a small percentage of that market share, it is still sizeable. In addition, some new OEMs like Th!nk have come up with factory models which are not land-intensive (<1 ha), which would make even car assembly possible in Singapore.

We have been trying to anchor more automotive component manufacturing and R&D in Singapore. Considering the strong synergies between EV components and regular electronics components, EVs could be an area for Singapore-based electronics fabs and suppliers to diversify into. Many of the EV component suppliers are also start-ups, and hence may not have entirely internationalized their operations. Singapore may thus be a good starting point. To anchor the high value components like the battery, we will need to build a strong value proposition, be it in establishing a good supply chain for battery / battery management system components or a strong R&D infrastructure into new materials or manufacturing processes.

3.7.3.3 Eco-city management

Source: The comeback of the electric car?, Boston Consulting Group, 2009
Under the eco-city management sub-program, the following research areas are proposed:

- **Integrated Systems for City Management and Modelling**

  Given that sustainability challenges are interconnected, an integrated and holistic view of multiple variables is needed. This is where integrated IT systems can play a part to actively monitor, communicate, and help city planners to optimise key city variables such as energy and water usage, congestion and air pollution. These systems can predict and forewarn city authorities of impending crises, as well as undertake diagnostic and remediation functions automatically to protect and ensure the safety, health and well-being of its inhabitants.

  City management requires the “de-siloing” and integration of multiple and interconnected factors. Hence there is also a rising need for modelling and simulation systems to help city planners predict and test response and remediation functions. Effective models, such as catastrophe and epidemic risk management models, are necessary to allow governmental authorities to manage socio-political and financial risks in their decision making.

- **Public Security**

  Another aspect of urban sustainability is in the area of public security. As cities become more densely populated, well-connected and open, potential threats to personal and national security take on an elevated scale. Especially in the years since the 9/11 incident, domestic, cross-border and international terror threats have emerged. Hence the protection of transportation, infrastructure, and strategic assets has become a topmost national priority. The range of urban security concerns include:

  - National security: related to terrorism, crimes and health epidemics
  - Business safety: related to systems and document confidentiality
  - Financial security: including financial fraud
  - Internet security: related to virus and network intrusions
  - Personal security: concerning physical safety and identity theft

  Similarly in this area, systems are being developed that can integrate existing surveillance capabilities with highly sophisticated situational awareness and command and control centres. These systems also work in collaboration with law enforcement, traffic management and general security procedures in urban domains. Increasingly, information systems are seen as a tool to empower law enforcement forces, first responders, emergency services and even municipal authorities.
3.7.4 R&D capabilities available and needed

Although it is clear that the research areas proposed under the Eco-city program are also being pursued by a large number of countries and research organizations (both public and private) around the world, A*STAR and other Singapore research institutions have strong core capabilities as well as application/domain-specific research capabilities and activities that can be leveraged upon to execute a competitive and productive research program.

For example, broad capabilities in ICT and embedded systems are available at I2R and SIMTech. Advanced sensors and measurement technologies are being researched in a number of RIs, including DSI, IME, IMRE, SIMTech and I2R.

Technologies for smart grids and microgrids, including power electronic interconnection technologies are the focus of the newly established EPGC, who are working with partners both within A*STAR and outside (IHLs and industry) to develop relevant capabilities and projects. Other capabilities in analysis and modeling, and system control and management are also being developed at the Centre.

A*STAR programs and consortiums such as A*CAR, IEDS, HOME2015 and STARhome are already providing strong foundations and capabilities for research under this program.

Through national level task forces on Electric Vehicles and Intelligent Urban Energy Systems, key stakeholders in government and industry are being engaged to identify and initiate potential R&D collaboration areas that would help attract and anchor new economic activities and investments in Singapore.

3.7.5 Recommended programme roadmap and milestones

Many of the technologies under this program can be developed for commercial use over the short term (< 5 years), while others may see commercial viability only in the medium term (5-10 years).

The research roadmap and milestones for this programme will have to be developed further if the programme is accepted for implementation.

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36 A particularly ambitious project is the Masdar Initiative, which includes Masdar City, targeted to be the world’s first zero energy and zero waste city.


Chapter 4
Conclusion

The Sustainable Development panel adopted the Siemens’ Picture of the Future (PoF) process for this STVC 2015 research programme identification exercise. Based on the PoF methodology, we defined our panel’s scope and the trends associated with it. In the process, we identified user segments, functions, living spaces that are related to each of the identified trends. Sub-groups for each of the proposed innovations and the technologies were formed, and technologies verified with potential relevant users. The proposed programmes were prioritized based on the scoring criteria listed below:

- Size (in terms of resources needed)
- Cross Discipline
- Use-Oriented (User Validated)
- Economic Impact
- National Interest
- (SERC) Niche with respect to other organizations performing sustainable development R&D
- Novelty
- Technical Challenge
- Leveraging on current capabilities

A total of 7 research programmes, which constitute the potential technologies that can be developed by SERC under the Sustainable Development theme were identified. They are:

- Waste Management
- Sustainable Manufacturing
- Sustainable Fuels, Chemicals and Materials
- Solar PV
- Green Buildings
- Energy Storage
- Intelligent Eco-city Infrastructure &Systems

These research programmes are discussed in detail in Chapter 3 of this report. With the inputs from the relevant users, the economic and technological opportunities and impacts for each of the programmes are presented. The assessment and stock take of R&D capabilities needed are also discussed. In addition, the proposed roadmap and milestones for several programmes are offered.
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Environment & Water Industry Development Council, Sustainable Development Task Force (under the Singapore Standards Council, and Green IT Task Force.)