INDUSTRY ENERGY EFFICIENCY

Technology Roadmap

EXECUTIVE SUMMARY

Singapore's manufacturing industry sector is an important part of Singapore's economy contributing to about 20% of Singapore's GDP and employs a fifth of Singapore's workforce. It has strong linkages with the service sector. The manufacturing sector is also expected to account for about 60% of Singapore's projected 2020 greenhouse gas emissions. Given the lack of access to alternative energy, energy efficiency is the primary strategy to reducing emissions.

Research, development, demonstration and deployment (RDD&D) of technologies is key to improving energy efficiency. The roadmap was developed by ICF International. Presented in this report are findings from analyses carried out by ICF International from August 2013 to January 2015.

This Roadmap identifies and describes the technological potential and opportunities to reduce energy use from business-as-usual levels up to 2030. It serves as a reference to provide guidance and insight to policy makers, industry leaders, academia and research institutes and other relevant stakeholders. It is also aims to facilitate greater collaboration among key stakeholders.

The Roadmap addresses the following subsectors and technology areas: 1) Petrochemical and chemicals (which will be abbreviated to "Chemicals" in the report), 2) Petroleum Refining, 3) Semiconductors, 4) Pharmaceuticals and 5) Generic technologies that cut across multiple sectors. These subsectors and technologies represent 70%-75% of the industry sector's current annual energy consumption.

A total of 30 emerging and next generation technologies, and 167 best available technologies and practices (BAT) were prioritised and their potential for reducing industrial energy use and CO_2 emissions were estimated.

The 30 emerging and next generation technologies are estimated to have technical potential energy savings of 5.7% in 2030. This is in addition to a technical potential energy savings of 13.1% from best available technologies (BAT) that are currently not utilized in industry. The corresponding potential 2030 emissions reduction from emerging and next generation technologies is estimated to be 6.2%, and 14.2% from BAT.

[1] Savings from the Reference Case ('reference'), where new energy efficiency market interventions are absent after 2010.

Summary of Selected Emerging and Next Generation Technologies

Technology Name	Subsector	Technical Potential for reduction of subsector energy use (%)	Technical and Market Risks	Follow-up Actions
Improved Catalysts	Refining and Chemicals	2.9%	• Impact on process unknown • RDD&D organisational alignment needed • High initial investment	• Research Programs • International Collaborations • Alternative Financing Schemes
Refinery and Chemical Plant Integration	Refining and Chemicals	1.4%	• Lack of inter-organisational collaborations • Unfavorable policies / regulations • Impact on process unknown	• Technology RDD&D Centers • New Shared Risk Framework • Demonstrations
Super-critical CO_2 Cycle Heat Recovery Systems and Other Low Grade Waste Heat Recovery Systems	Refining and Chemicals	0.8%	• Unproven technology • Complexity of Targeted Processes • Unattractive ROI / high investment • Low efficiency requires lot of heat • Limited Financing for RDD&D	• Research Programs • International Collaborations • Demonstrations • Technology Deployment Programs • Alternative Financing Schemes • Demonstrations
Utility Optimization through Advanced Control Systems	Chemicals	0.2%	• Impact on process unknown • High initial investment • Perception that utilities are already optimised	• Technology Deployment Programs • Alternative Financing Schemes • Case Studies/Share Best Practices
Advanced Product and Process Control	Semi-conductor	4.9%	• Impact on process unknown • Limited O&M support in region • Unattractive ROI / high investment	• Technical Assistance • Technology Deployment Programs • Alternative Financing Schemes

Ultra-pure Water Generation Technology (Reverse Osmosis with Electro-Deionisation)	Semi-conductor	4.6%	• Unproven technology • Unattractive ROI / high investment • Uncertainty about economic stability	• Research Programs • International Collaborations • Financial Incentives
Super High Efficiency Nitrogen Plant	Semi-conductor	1.6%	• Technical barriers yet to be overcome • Competing RDD&D priorities • Small Potential for Scalability in Singapore	• Research Programs • International Collaborations • Financial Incentives
Advanced Process Heater	Generic (All)	0.2%	• Unproven technology • Unattractive ROI / high investment • Require substantial changes to existing plant infrastructure	• Technology Deployment Programs • Alternative Financing Schemes • Case Studies/Share Best Practices
Smart Manufacturing/ Advanced Facility Automation	Generic (All)	0.3%	• Require substantial changes to existing plant infrastructure • Limited application expertise in Singapore • High initial investment	• Financial Incentives • Industry Collaboration/ Investment • Case Studies/Share Best Practices

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1 INTRODUCTION TO SINGAPORE'S EE TECHNOLOGY ROADMAP FOR INDUSTRY

1.1 Current Energy Use and CO2 Emissions by the Industry Sector

Singapore's industry sector (hereby also referred to as the 'sector') is an important contributor to economic growth and was responsible for 19% of Singapore's gross domestic product in 2010. Major industries include refining, petrochemical, specialty chemicals, pharmaceuticals, and semiconductors. Other industries include, food and beverage, printing, medical technology, marine and offshore engineering, and precision engineering.

The sector consumed over 87% of all natural gas used in end-use sectors and 40% of all electricity in 2010 (EMA, 2012). Under the business-as-usual (BAU) scenario, the industrial sector is projected to account for 60% of Singapore's CO_2 emissions in 2020 (Figure 1).

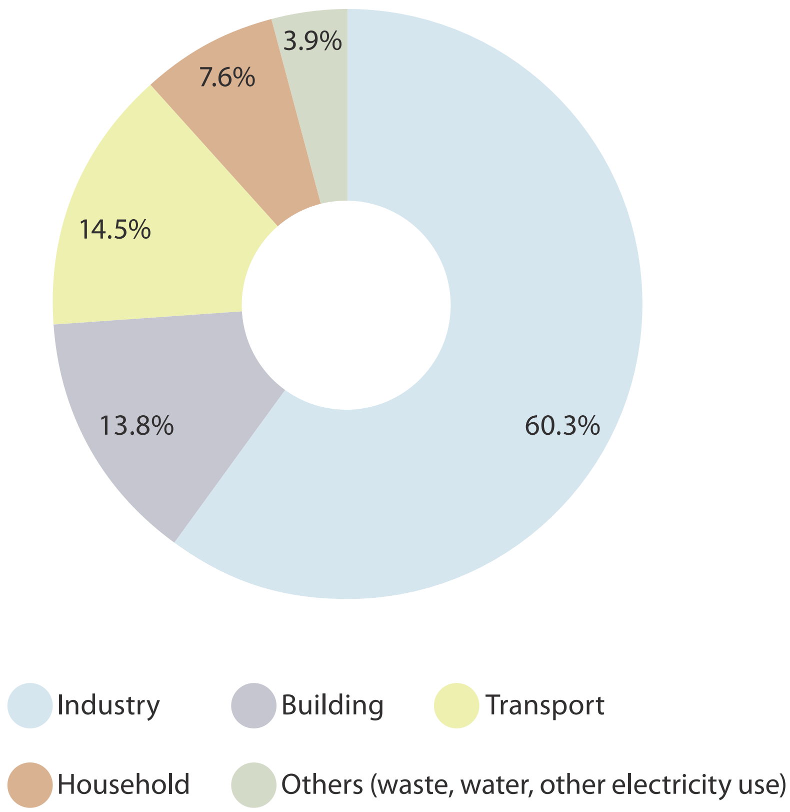


Figure 1: Singapore projected 2020 BAU emissions

Energy efficiency (EE) has been identified as a core strategy to reduce emissions (NCCS 2012). Demand-side management of energy represents an important opportunity for Singapore to further reduce emissions while reducing total energy costs and improving industrial competitiveness. Apart from deploying best-available technologies (BAT), research, development, demonstration and deployment (RDD&D) of new emerging and next generation technologies can play an important role in improving industrial energy efficiency.

1.2 Major Subsectors and Energy Consumption Profiles

The chemicals and petroleum refining subsectors are the leading industrial energy consumers[1], contributing to the bulk of CO_2 emissions (Figure 2 and 3). Continued growth in the sector is expected, which will drive growth in energy consumption and CO_2 emissions.

Figure 2: Primary energy use by subsector in 2010

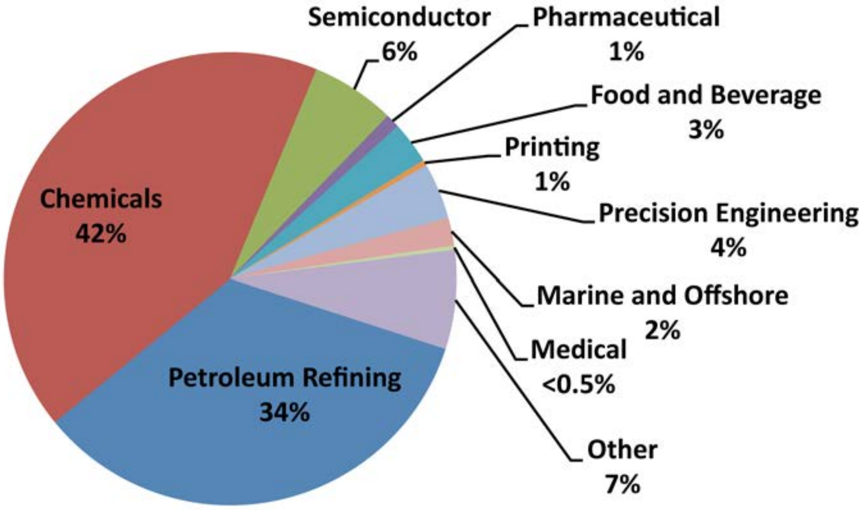
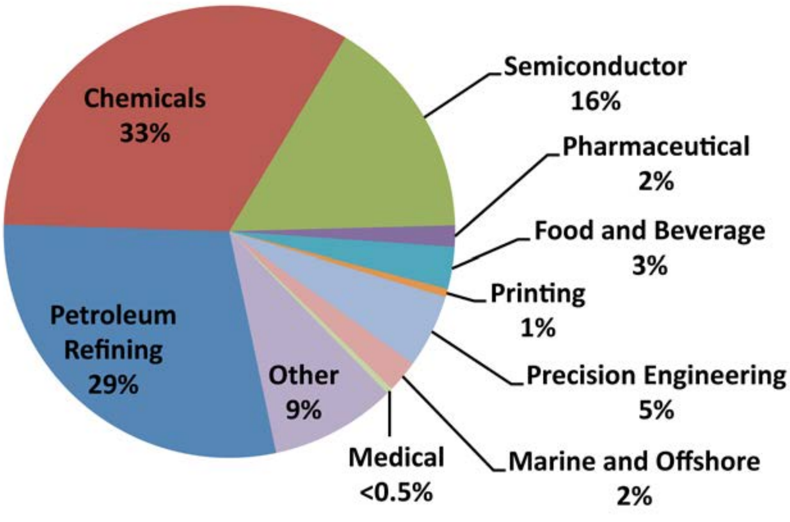


Figure 3: CO_2 emissions by subsector in 2010



To identify energy efficiency opportunities, we start by identifying the most energy-intensive end-uses from industry energy profiles. Energy consumption by end-use varies across the sector (See Figure 4 to Figure 7).

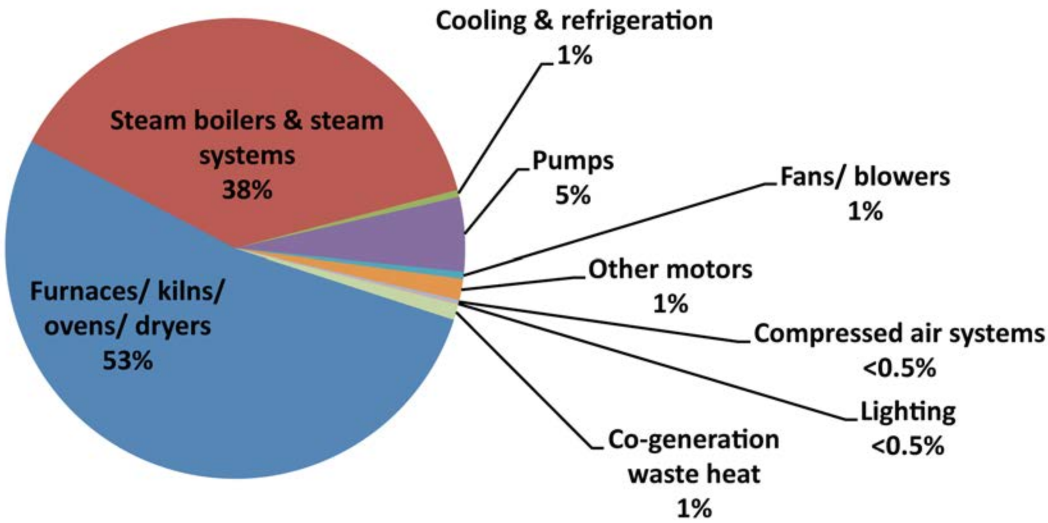
[1]Throughout the report, references to "petroleum" and "petroleum refining" are used interchangeably. References to "chemicals" should be interpreted to include "petrochemicals" and "specialty chemicals".

Petroleum Refining Subsector

The petroleum refining subsector is concentrated in and around Singapore's chemicals and energy hub on Jurong Island, enabling integration with chemical facilities and providing several key advantages. It is expected that the petroleum refining subsector will continue to improve its efficiency to compete with new refineries being constructed globally. Key challenges to the growth of the subsector include high energy prices and increasing regional competition.

The petroleum refining subsector in Singapore consists of three facilities located on or adjacent to Jurong Island. In 2010, the petroleum refining subsector represented 34% of total industry sector energy consumption and 29% of total industrial sector carbon dioxide emissions (Figure 2 and 3). Surveys and modeling carried out for this study determined that furnaces and steam boilers/ steam systems are the highest consuming end-uses within this subsector in 2010, representing 53% and 38% of subsector energy consumption, respectively (Figure 4).

Figure 4: Petroleum refining energy use profile by end-use (2010)

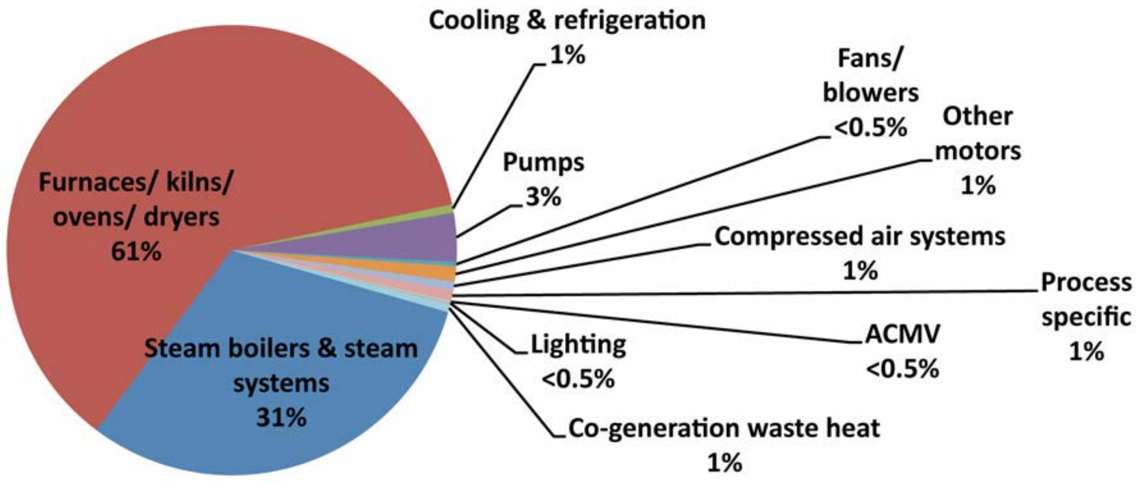


Chemicals Subsector

The petrochemical and chemicals subsector (abbreviated in this report to "chemicals") is clustered in close proximity, as part of Singapore's chemicals and energy hub on Jurong Island, enabling synergies with petroleum refiners and providing several key advantages. It is expected that the industry in Singapore will continue to shift more emphasis towards specialty chemical production and higher value products. Similar to the Petroleum Refining subsector, key challenges to the growth of the subsector include high energy prices and increasing regional competition.

In 2010, the chemicals subsector accounted for 42% of total industry sector energy consumption and 33% of total industry sector carbon dioxide emissions (Figure 2 and 3). Furnaces and steam boilers/steam systems are the highest consuming end-uses accounting for 61% and 31% of subsector consumption respectively (Figure 5).

Figure 5: Petrochemical and chemicals energy use profile by end-use (2010)

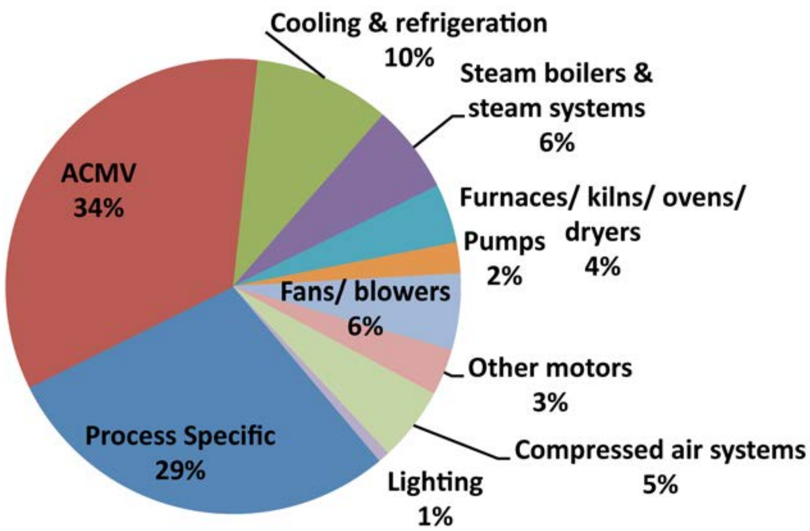


Semiconductor Subsector

The semiconductor subsector contributed 5.3% of Singapore's GDP in 2014. The semiconductor subsector must manage rapid changes to product lifecycles and comply with strict product specifications required by customers.

The semiconductors industry consists primarily of 7 companies with multiple facilities located throughout Singapore. In 2010, the semiconductor subsector accounted for 6% of total industry sector energy consumption and 16% of total industry sector CO_2 emissions (Figure 2 and 3). ACMV (air-conditioning and mechanical ventilation, 34%), process specific (29%), and cooling and refrigeration (10%) are the highest energy consuming end-uses in the subsector (Figure 6).

Figure 6: Semiconductor energy use profile by end-use (2010)



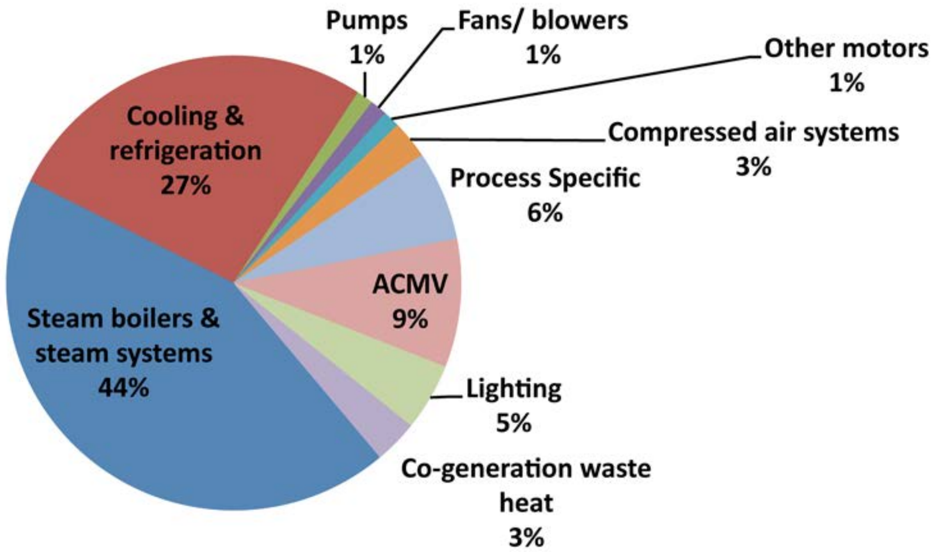
Pharmaceutical Subsector

Singapore is considered the pharmaceutical hub of Southeast Asia with more than 30 leading pharmaceutical and biomedical science companies with established regional headquarters. The pharmaceutical industry is of strategic importance to Singapore and is poised for significant growth. It is expected that growth and development will center on biologics manufacturing and process control and optimisation. It is key, however, to consider the emerging and next generation technologies in the context of the industry, which is heavily regulated and focused on new product development.

The pharmaceutical industry in Singapore consists of pharmaceutical plants, leading biopharmaceutical manufacturing companies and medical technology manufacturers located in the Tuas Biomedical Park.

In 2010, the pharmaceutical subsector accounted for 1.3% of total industry sector energy consumption and 1.5% of total sector greenhouse gas emissions (Figure 2 and Figure 3). Steam boilers and steam systems (43%), cooling and refrigeration (27%), ACMV (9%), and process specific (6%) end-uses are the highest energy consumers in the subsector (Figure 7).

Figure 7: Pharmaceutical energy use profile by end-use (2010)



1.3 Scope of Roadmap

The Industry EE Technology Roadmap addresses the following industry subsectors and technology areas: 1) chemicals, 2) petroleum refining, 3) semiconductors, 4) pharmaceuticals and 5) generic technologies.

'Generic technologies' are technologies that apply across all industrial subsectors. These include pumps, fans, compressed air systems, utility furnaces and steam systems.

This roadmap examines technologies in the research, development, demonstration and early deployment (RDD&D) stages, in addition to currently best available technologies (BAT). RDD&D technologies are categorized as Next Generation (representing those at TRL 1-5) and Emerging (representing TRL 6-9), as illustrated in Figure 8 and Table 1. Greater focus is on those technologies that address energy-intensive end-uses and that are expected to have substantial impacts on energy consumption and emissions reductions in the longer-term post-2020 timeframe.

Figure 8: Next generation and emerging technologies within the TRL spectrum

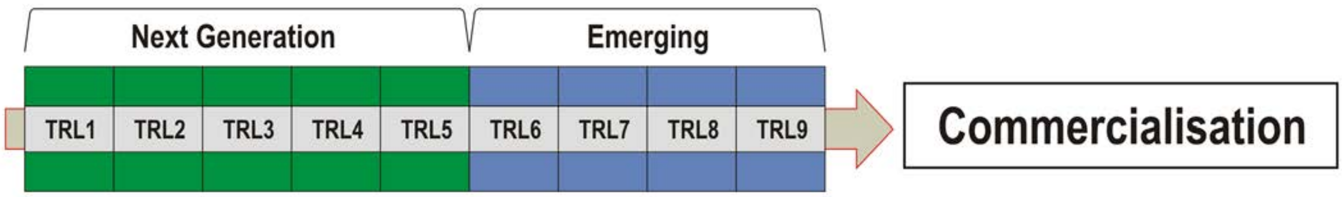


Table 1: Technology Readiness Level (TRL) definitions used in the Singapore industry EE roadmap

Next Generation Technologies (Basic/Applied Research, Prototype Development)	Emerging Technologies (Demonstration/ Deployment)
TRL 1: Basic research	**TRL 6:** Prototype system verified
TRL 2: Applied research	**TRL 6:** Prototype system verified
TRL 3: Critical function or proof of concept established	**TRL 7:** Integrated pilot system demon-strated
TRL 4: Lab testing/validation of components/ processes	**TRL 8:** System incorporated in commer-cial design
TRL 5: Lab testing of integrated/semi-integrat-ed system	**TRL 9:** System proven and ready for full commercial deployment

1.4 Objectives of Technology Roadmap for Singapore's Industrial Sector

This roadmap describes technology opportunities for energy efficiency improvement in Singapore's industries. It serves as a reference to provide guidance and insight to policy makers, industry leaders, academia and research institutes and other relevant stakeholders. It is also a step to enhance collaboration among key stakeholders.

Energy use and emissions from the industry sector are expected to increase with economic growth and it is the objective of this analysis to determine the key emerging and next generation opportunities that have the potential to reduce both energy consumption and carbon dioxide emissions.

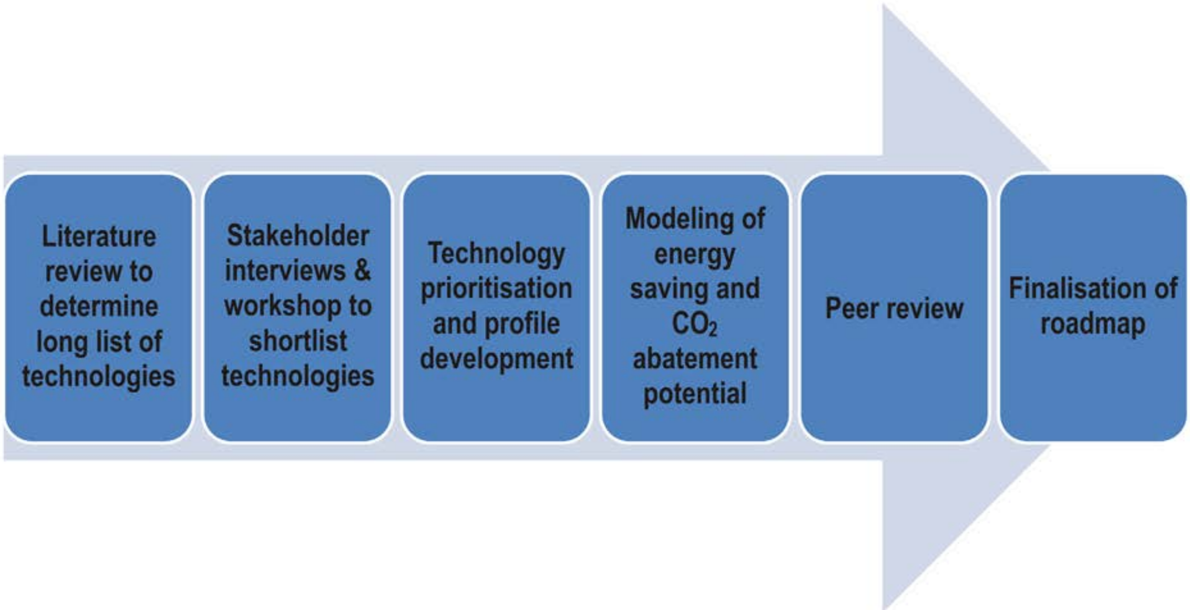
2 Development of Technology Roadmap

2.1 Technology Assessment

This roadmap was developed in parallel with the study of energy and CO_2 reduction potentials for the entire industry sector. Information from site visits and end-use analyses were used as one of the inputs guiding the selection of technologies to be included in the roadmap.

The activities carried out to prioritise technologies are shown in Figure 9. Presented in this report are findings from analyses carried out by ICF International from August 2013 to January 2015.

Figure 9: Development process for the Singapore Industry EE Technology Roadmap



The technologies included in the roadmap focused on the areas with the greatest energy saving and CO_2 abatement potential. One screening criterion used to prioritise technologies for the roadmap was a focus on measures that target savings in the end-uses found to have the highest energy use in Singapore's industries. While not always the case, the end-uses or processes consuming the most energy often have the greatest potential for energy savings.

Local and international stakeholders from industry and academia were significant contributors to the development of the roadmap. Stakeholder input led to the list of technologies that were first included in the roadmap, and stakeholders reviewed detailed technical profiles[2] that were used to characterise the technologies in the potential model. Roadmap technologies prioritised and vetted by stakeholders were integrated into a model to develop an estimate of their energy and CO_2 reduction potential from initial market penetration from 2010 to 2030 within relevant subsectors.

The potentials of emerging and next generation technologies were also reviewed by Singapore and international experts from industry, government and academia.

[2] Efficiency improvement potential, service life, cost of equipment, timeline and risk factors for development & deployment, possible interventions to support development and deployment.

It should be noted that technologies not addressed in this roadmap, but which are developed after its publication, could provide additional potential and should be prioritised based on the energy-intensive end-uses within the subsector. Potential exists for additional, new or alternative RDD&D technologies to reduce consumption and CO_2 emissions above and beyond the levels identified in this study.

2.2 Modeling of Energy Saving Potential of Technologies

The performance profiles of the prioritised technologies were integrated into technical and economic potential models to determine maximum potential energy savings from business-as-usual levels, and savings most likely to occur due to economic conditions that exist when the technologies enter and drive through the market, respectively.

The model involves four main steps:

1. Define base year (2010) energy end-use profile.
2. Project energy use up to 2030, in the absence of any new energy efficiency market interventions after 2010. This is referred to as the Reference Case ('reference'), which is the baseline against which potential energy savings are calculated.
3. Identify possible energy efficiency opportunities, through a combination of literature and expert reviews (Figure 9).
4. Estimate the implementation rate and remaining potential for implementation of the identified energy efficiency opportunities, through industry survey and expert review.
5. Calculate potential energy savings below Reference Case levels by multiplying the end-use energy use by the opportunity savings and by the percent of remaining implementation potential.

The technical and economic potential model calculates the cumulative effect of implementing all technologies, rather than just looking at one measure in isolation, taking into consideration the interactive effects between measures (i.e. available energy to be saved is reduced with each subsequent opportunity implemented, known as the cascading effect). The technical potential estimates the level of energy savings and carbon dioxide abatement that would occur when all industrial processes, equipment and buildings are upgraded with EE measures that are technically feasible, regardless of any other constraints, such as cost and economic constraints. Due to the cascading effect, the energy savings per technology calculated in the potential model are less than the sum of technical potential savings that would occur if each technology were implemented in isolation.

The economic potential estimates the level of savings that would occur if all current equipment/ processes were replaced by best available technologies/practices (BAT) with positive net present values (NPV) at 2010. For Best Available Technologies (BAT) only technologies and practices that are technically feasible and commercially available at the base year of 2010 were included in the analysis. Emerging and next generation technologies were included after 2010 based on when the technologies are expected to be commercialized. Based on the net cost, fuel and CO_2 savings values of the technologies were developed for 2030.

3 Technology Opportunities in EE Improvement

3.1 Overview of Industry Sector

A total of 30 emerging and next generation technologies, and 167 best available technologies and practices (BAT) were prioritised and their potential for reducing industrial energy use and CO_2 emissions were estimated.

- **Technical Potential:**
  - By 2030, industry-wide energy consumption could be reduced from the reference by:
    - 13.1% from currently available technologies and practices
    - 5.7% from emerging and next generation technologies and practices
  - By 2030, industry-wide CO_2 emissions could be reduced from the reference by:
    - 14.2% from currently available technologies and practices
    - 6.2% from emerging and next generation technologies and practices
- **Economic Potential:**
  - By 2030, industry-wide energy consumption could be reduced from the reference by:
    - 11.3% from currently available technologies and practices
    - 5.1% from emerging and next generation technologies and practices
  - By 2030, industry-wide CO_2 emissions could be reduced from the reference by:
    - 12.4% from currently available technologies and practices
    - 5.6% from emerging and next generation technologies and practices

The largest technical and economic potentials from emerging and next generation technologies are listed in Table 2 and Table 3. Figure 10 shows the energy savings contribution by subsector.

Figure 10: 2030 Technical potential energy savings contribution, by subsector

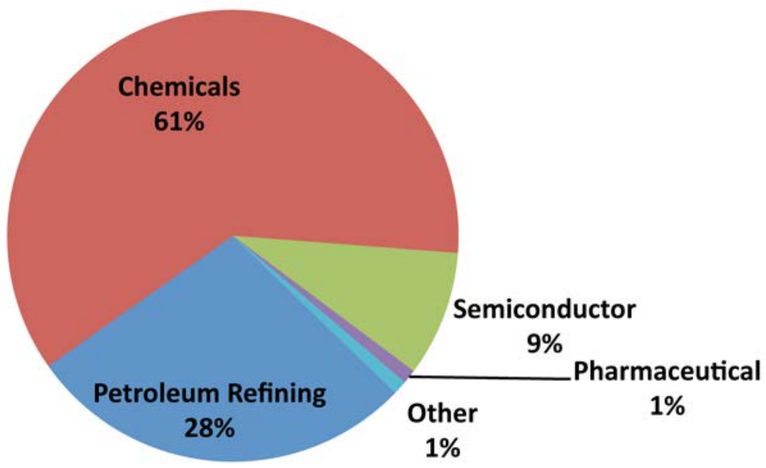


Table 2: Potential reduction of energy use from reference levels through the implementation of BAT and Emerging / Next generation (NG) technologies, estimated for various end-uses by 2030.

End-use	Technical Potential (%)		Economic Potential (%)	
	BAT	Emerging/NG Technologies	BAT	Emerging/NG Technologies
Steam boilers and steam systems	9.7%	0.4%	7.3%	0.2%
Hot water systems	7.0%	-	7.0%	-
Furnaces / kilns / ovens / dryers	12.5%	5.2%	11.7%	4.3%
Cooling and refrigeration	17.9%	1.0%	16.7%	-
Pumps	11.7%	0.1%	11.4%	0.0%
Fans/blowers	8.5%	0.1%	7.8%	0.0%
Other machine drives	5.1%	0.1%	4.8%	0.0%
Compressed air systems	17.3%	-	15.0%	-
Process specific	9.4%	14.1%	8.0%	14.1%
ACMV	32.0%	0.1%	32.0%	-
Lighting	29.4%	-	29.4%	-
Other	-	-	-	-
System	1.2%	2.5%	0.8%	2.4%
Overall reduction in sectoral energy use	13.1%	5.7%	11.3%	5.1%

Table 3: Technical potential of selected emerging and next generation technologies when implemented across Singapore's industry

Technology Name	Subsector	Technical % reduction in sub-sector energy use
Improved catalysts	Refining and chemicals	2.9%
Refinery and chemical plant integration	Refining and chemicals	1.4%
Super-critical CO_2 cycle heat recovery systems	Refining and chemicals	0.6%
Low grade waste heat recovery (WHR)	Refining and chemicals	0.2%
Utility optimisation through advanced control systems	Chemicals	0.2%
Advanced product and process control	Semi-conductor	4.9%
Ultra-pure water generation technology (Reverse osmosis with electro-deionisa-tion)	Semi-conductor	4.6%
Super high efficiency nitrogen plant	Semi-conductor	1.6%
Advanced process heater	Generic (All)	0.2%
Smart Manufacturing / advanced facility Automation	Generic (All)	0.3%

Table 4 summarises the technical potential energy savings for the 4 major subsectors that can be achieved by 2030 through the deployment of BAT, emerging and next generation technologies.

Table 4: Potential reduction in energy use by BAT and Emerging/Next Generation technologies by subsector (2030)

End-use	Technical Potential (%)		Economic Potential (%)	
	BAT	Emerging/NG Technologies	BAT	Emerging/NG Technologies
Petroleum	18.5%	4.1%	17.2%	2.8%
Chemicals	6.8%	6.1%	5.3%	6.0%
Semiconductor	21.1%	12.0%	20.7%	11.6%
Pharmaceutical	21.1%	2.4%	20.6%	2.2%

3.2 Petroleum Refining Subsector

Furnace and steam system end-uses are the largest consumers of energy in the petroleum refining subsector. Energy consumption in both these end-uses remains large even with BAT. Therefore, technologies related to furnaces and boilers/steam systems should be prioritised, as well as plant-wide or process specific technologies which will achieve significant savings in these end-uses. The following key process types, as well as utilities, were prioritised areas which would produce the most overall impact in the subsector:

- System-Wide
- Crude Distillation Unit
- Hydrogen Generation
- Distillation

The technical potential estimates the level of energy savings and carbon dioxide abatement that would occur when all industrial processes, equipment and buildings are upgraded with EE measures that are technically feasible, regardless of any other constraints, such as cost and economic constraints. The economic potential estimates the level of savings that would occur if all current equipment and processes were replaced by best available technologies and practices (BAT) with positive net present values (NPV) at 2010. Together, BAT, emerging and next generation technologies have the technical potential to reduce the subsector's energy use by 22.6% by 2030 (Table 5).

- **Technical Potential:**
  - By 2030, refining subsector energy consumption could be reduced by:
    - 18.5% from currently available technologies and practices
    - 4.1% from emerging and next generation technologies and practices
  - By 2030, refining subsector CO_2 emissions could be reduced by:
    - 19.1% from currently available technologies and practices
    - 4.7% from emerging and next generation technologies and practices

- **Economic Potential:**
  - By 2030, refining subsector energy consumption could be reduced from the reference by:
    - 17.2% from currently available technologies and practices
    - 2.8% from emerging and next generation technologies and practices
  - By 2030, refining subsector CO_2 emissions could be reduced from the reference by:
    - 18.0% from currently available technologies and practices
    - 3.4% from emerging and next generation technologies and practices

The largest potential is estimated to be for technologies that reduce the energy use in total plant (system end-use) and to reduce energy use for heating (boilers/steam systems and furnace end-uses), such as refinery and chemical plant integration, improved catalysts and super-critical CO_2 cycle heat recovery systems (Tables 5-7, Figure 11).

Table 5: Potential reduction in energy use by BAT and emerging / next generation technologies within specific end-uses in 2030 (Petroleum subsector)

End-use	Technical Potential (%)		Economic Potential (%)	
	BAT	Emerging/NG Technologies	BAT	Emerging/NG Technologies
Steam boilers and steam systems	9.6%	-	8.0%	-
Furnaces	25.2%	3.6%	24.0%	1.0%
Cooling and refrigeration	2.0%	-	1.4%	-
Pumps	9.4%	-	9.1%	-
Fans/blowers	6.1%	-	6.1%	-
Other machine drives	3.8%	-	3.8%	-
Compressed air systems	22.2%	-	22.2%	-
Lighting	5.0%	-	5.0%	-
System	1.0%	2.3%	1.0%	2.3%
Overall reduction in Petroleum energy use	18.5%	4.1%	17.2%	2.8%

Figure 11: Petroleum refining: 2030 technical potential energy savings

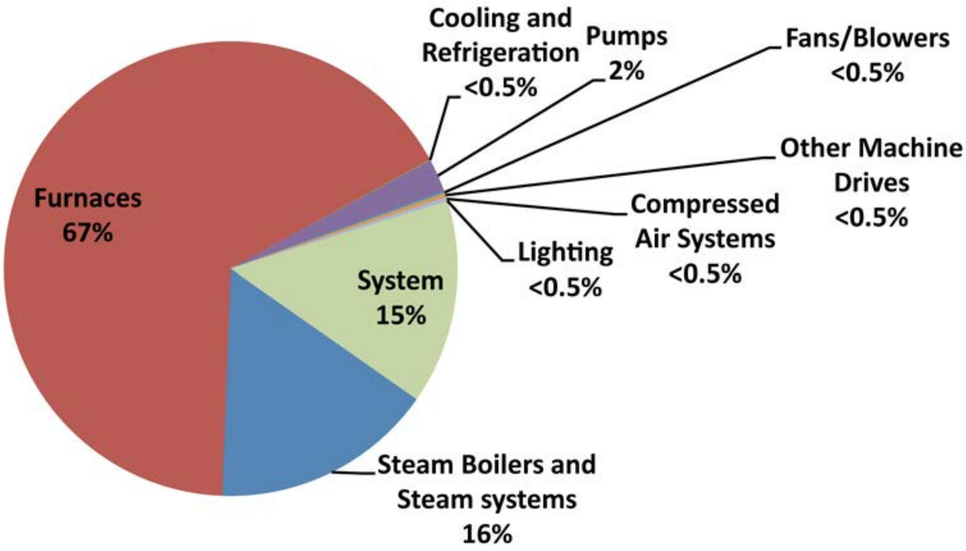


Table 6: Petroleum subsector top BAT opportunities (2030)

BAT	Technical Potential Savings (within subsector)	
	Energy	CO_2
Combustion optimisation (furnace)	4.9%	5.1%
Advanced heating and process control (furnace)	2.7%	2.9%
Preventative furnace maintenance	1.4%	1.5%
Insulation (furnace)	1.2%	1.3%

Table 7: Potential energy and emission savings by top emerging/ next generation technologies in 2030 (Petroleum subsector)

Emerging / Next Generation Technology	Technical Potential Savings (within subsector)	
	Energy	CO_2
Refinery and chemical plant integration	1.5%	1.5%
Improved catalysts	1.7%	1.8%
Super-critical CO_2 cycle heat recovery systems	0.7%	1.0%
Crude distillation pre-heat improvement	0.1%	0.1%
Low grade waste heat recovery (WHR)	0.1%	0.1%
Total reduction	4.1%	4.5%

3.2.1 Description of Selected New Technologies

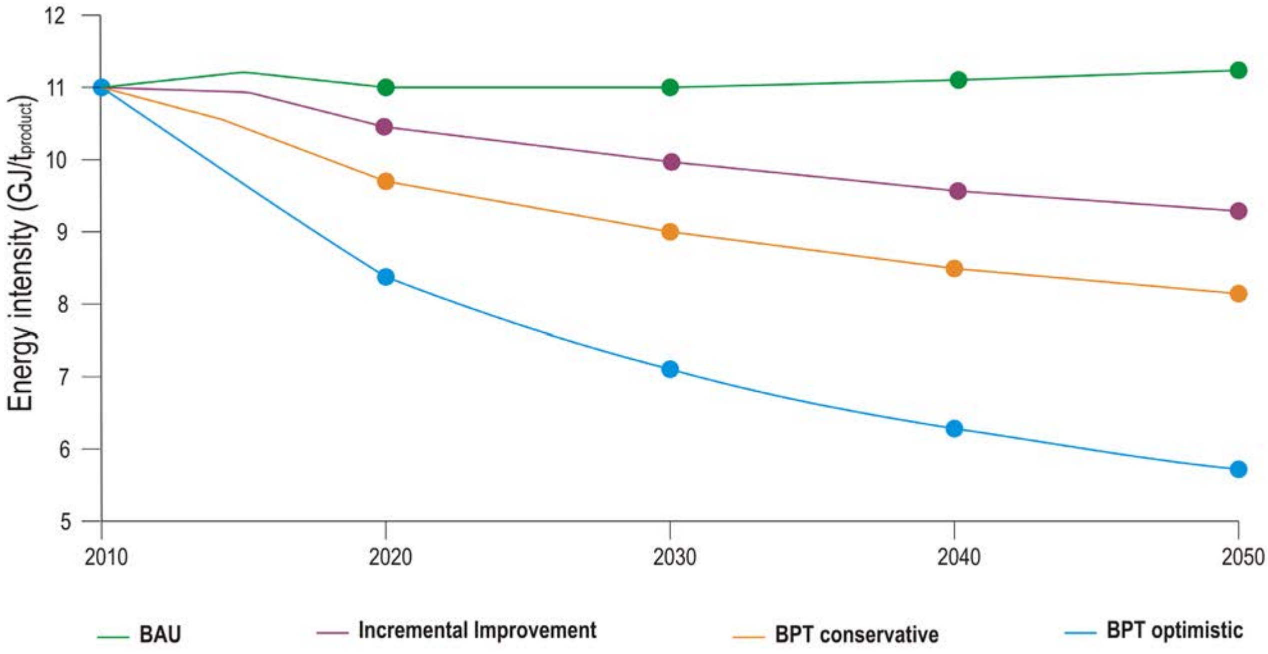
Improved Catalysts

A wide variety of catalysts are used for different refinery processes (cracking, reforming, hydrotreating, etc.), each with their own performance characteristics, and different potentials to be improved upon. Catalyst developments often focus on improving plant yield, but they also achieve greater energy efficiency by reducing the required levels of recycle, heating, and recompression energy. Where a new catalyst is used to improve energy efficiency and reduce carbon dioxide emissions, it is usually not implemented in an isolated manner, but is combined with corresponding process technology advances, such as a new reactor design (International Energy Agency, 2013).

Catalysts are essential to efficient production across many industrial sectors: some 90% of chemical processes employ catalysts, as do nearly all petroleum refining processes (Yoneyama, 2010). However, not all catalyst applications are focused on energy savings, and some have only indirect impacts on energy consumption.

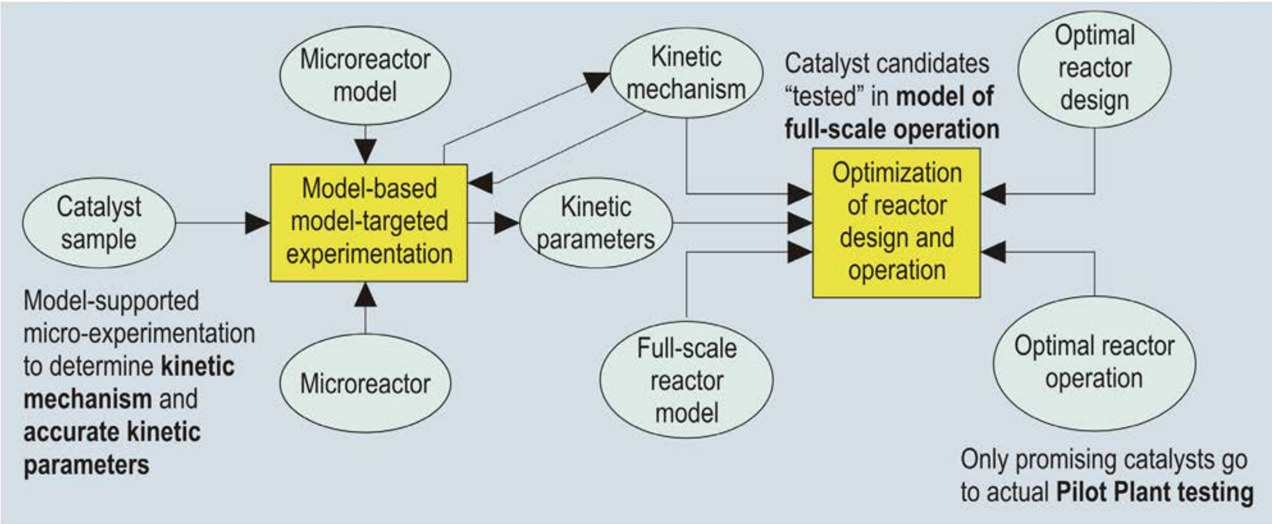
A 2013 IEA Chemical Industry Catalytic Process Roadmap (International Energy Agency, 2013) noted that constant improvement in catalytic processes is essential to reduce energy consumption in refineries (International Energy Agency, 2013). The IEA Roadmap modeled gradual catalyst driven efficiency improvements, based on data received from a survey of chemical manufacturers and feedback from other industrial experts. This chemicals roadmap also provided a rough estimate of changes to specific energy consumption (SEC) values for certain catalytic refining processes through catalyst improvements. The approximated industry wide improvements are shown in Figure 12.

Figure 12: Evolution of energy intensity for incremental improvements and deployment of best practice and established technologies in existing plants or new facilities (International Energy Agency, 2013)



Modeling advances allow for new catalyst applications to be tested more rapidly, through less expensive methods, with only the most promising catalysts advancing to actual pilot plant testing. The evolution of catalysts has been supported by improving modeling capabilities. For example, lower temperature and improved reactor layouts can be made possible through catalyst modeling. Figure 13 presents such a procedure for catalyst design and optimisation, with catalysts screened using models to minimise physical testing requirements.

Figure 13: Example of modeling steps for improved catalyst development (Bäumler, 2007)



The development and deployment of improved catalysts can achieve energy savings for petroleum refineries in Singapore by improving process operating conditions (lower temperature and/or pressure requirements) and increasing yield (reduced energy intensity). This measure applies broadly throughout the subsector as the majority of refinery processes use catalysts. However, while some applications require only a simple replacement of catalysts, other applications require novel reactors for the new catalysts.

The refining processes in Singapore that uses catalysts for their process to provide context on where improved catalysts can be applied:

- Catalytic cracking
- Catalytic reforming
- Catalytic hydrocracking
- Catalytic hydrotreating
- Alkylation
- Oxygenates production (MTBE)
- Claus process

Table 8 lists the top 20 chemical products in Singapore that use catalysts for their process.

Table 8: Catalyst use in top Singapore chemical processes

Chemical Product	Process Route
Polyethylene	Polymerisation
Polypropylene	Polymerisation

Chemical Product	Process Route
Benzene	Catalytic reforming, toluene hydrodealkylation, toluene dis-proportionation, or steam cracking extraction from gasoline (non-catalytic)
Styrene	Oxidation of propylene by ethylbenzene hydroperoxide in the styrene monomer/ propylene oxide (SM/PO) process
Propylene oxide	
Mono ethylene glycol	Produced from ethylene via ethylene oxide reacted with water, or the OMEGA Process
Xylenes	Methylation of toluene and benzene, or isomar process (also commonly extracted from catalytically reformed naphtha in an oil refinery)
Acetic acid	Carbonylation of methanol
Phenol	Partial oxidation of cumene (Hock Process)
Polystyrene	Cationic polymerisation
MTBE	Chemical reaction of methanol and isobutylene
Bisphenol-A	Condensation of phenol and acetone
Polyether polyols	Polymeric reaction
Methylmethacrylate monomer (MMA)	Oxidation of isobutylene followed by esterification
Oxo alcohol	Hydroformylation and hydrogenation
Acetone	Cumene process
Vinyl acetate monomer	Reaction of ethylene and acetic acid with oxygen

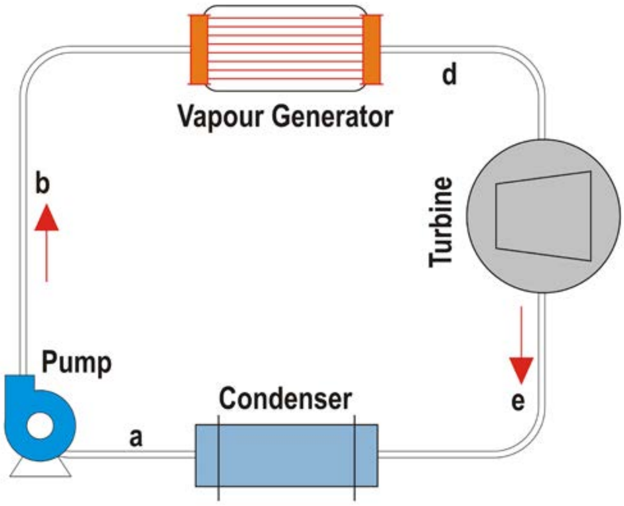
It should be noted that catalysts are not always developed to improve energy efficiency. While high efficiency catalysts directly reduce energy consumption, other catalyst improvements might focus on factors such as decreasing catalyst material costs, improving catalyst lifetime, and improving process yield. However, these other catalyst improvements may indirectly reduce energy consumption. For example, catalysts that improve yield will reduce the energy intensity of a process. Also, catalyst developments to allow longer lives or lower material costs may enable implementation of more efficient catalysts that were previously not feasible. Yield selectivity improvement remains the key to catalyst selection, and energy benefits are often side benefits of using more active catalysts.

Super-Critical CO_2 Cycle Heat Recovery Systems

Supercritical CO_2 (S-CO_2 systems have the potential to expand waste and exhaust heat recovery applications into broader markets than today's steam and Organic Rankine Cycles (ORC), through a combination of high efficiency, low cost, and small space requirements. Electricity generation from waste heat is one application of a potential game changing technology, which uses CO_2 in the supercritical state as the working fluid to achieve a more efficient thermodynamic cycle.

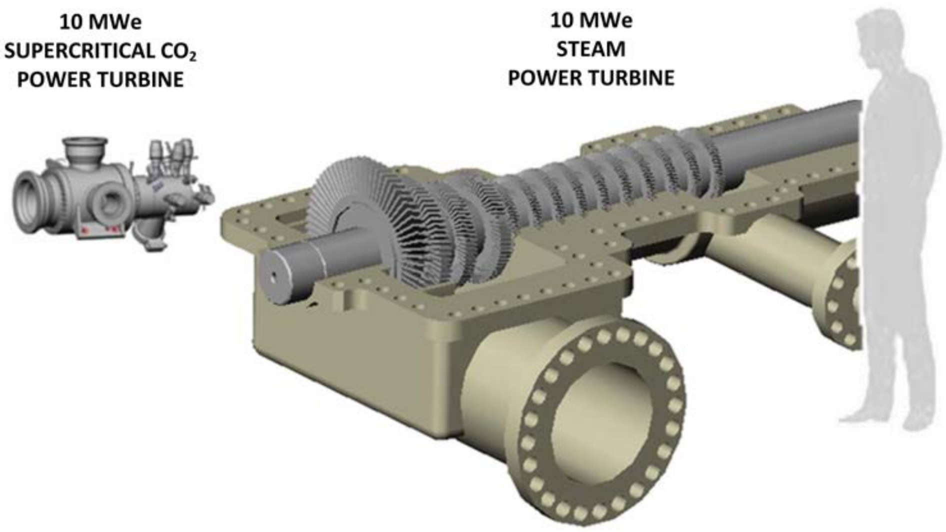
The overall cycle maintains the same elements of other Rankine cycles as discussed in the emerging waste heat recovery measure, and depicted in Figure 14.

Figure 14: Supercritical Rankine Cycle configuration (Chen, 2010)



S-CO_2 has a number of characteristics, such as its high power density, that make it more efficient than steam in a wide variety of turbine cycles. Carbon dioxide arrives at a supercritical fluid state when temperature and pressure reach their critical point (31°C/87°F at 73 atm) (Robb, 2012). In this state, it has gas and liquid qualities. Theoretically, any heat source above this temperature can sustain a S-CO_2 power generation cycle, whereas water requires much higher temperatures. While the basic cycle elements perform the same functions as in other Rankine cycles, the high power density means that the equipment sizes are greatly reduced from steam turbines, as shown in Figure 15.

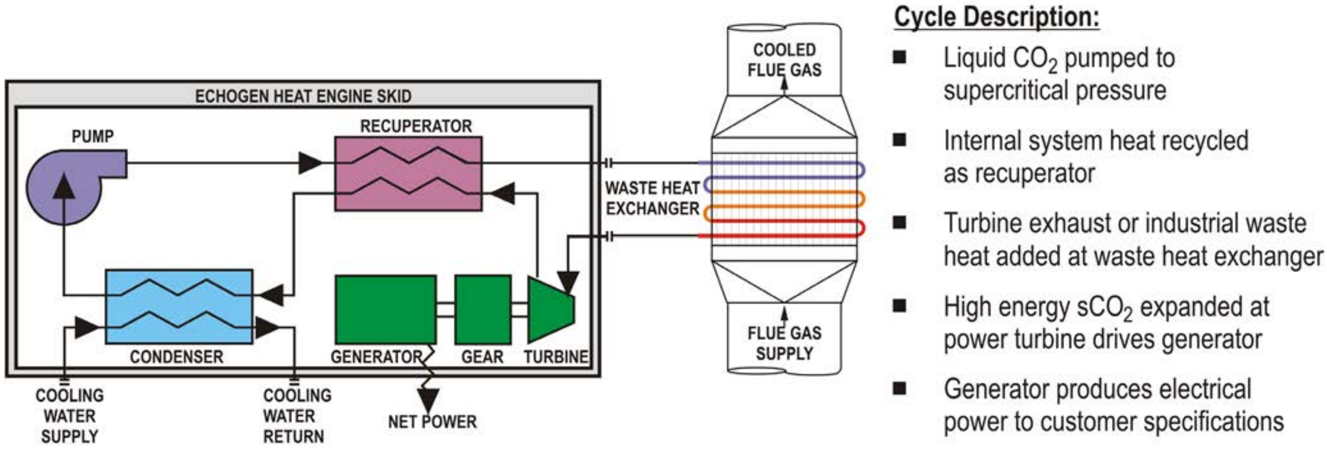
Figure 15: Comparison of expected equipment size (Persichilli, 2012)



Suitable fluids for these applications have relatively low critical temperatures and pressures, so they can be compressed and heated directly to their supercritical state before expansion, which enables a better thermal match with the heat source.

As the heating process of a supercritical Rankine cycle does not pass through a distinct two-phase region, unlike in Rankine cycles, there is better thermal match in the heat exchange and less irreversibility (Chen, 2010). Many major research bodies such as Sandia National Laboratories, Southwest Research Institute, and Lawrence Berkeley National Laboratory are placing a lot of emphasis on S-CO_2 (Robb, 2012). They are involved with companies such as Toshiba, Echogen, Dresser Rand, GE, Barber-Nichols, and Bechtel in creating these next-generation turbines (Robb, 2012). The proposed application of S-CO_2 cycles for heat recovery from one of those companies, Echogen Power Systems, is presented in Figure 16.

Figure 16: Proposed S-CO_2 cycle layout for heat recovery (Persichilli, 2012)



There is limited availability of information and different applications and configurations of the cycles under development (Robb, 2012). This suggests that the actual benefit of the S-CO_2 system is less than initially projected and there exist challenges of commercialising faced by manufacturers.

Other potential rival technologies, considered to be at lower TRL levels, include supercritical Rankine cycles with organic working fluids in place of CO_2 and technologies for Thermo-Electric Generation (TEG).

Advanced Separation

The abovementioned technologies are expected to be deployed by 2030. In addition, it should be highlighted that separation consumes a large portion of energy in both the petroleum refining and chemicals subsector, and disruptive technologies in this area offer promising savings post-2030. Dividing wall columns (DWC) is one improved type of distillation column. The technology of DWCs has been successfully introduced in industry for certain applications; however it is limited to three-component separation. On-going RDD&D on DWC will expand its use to multi-component mixtures.

There are several types of disruptive technologies in the RDD&D stage that are targeting distillation. These include much more aggressive heat pumping, novel expansion-compression cycles, absorption, adsorption and membrane solutions. One category of disruptive distillation technologies is isothermal separation, which involved technologies (such as membranes, absorption or adsorption technologies) that can avoid the heating and subsequent cooling. Hybrid separation process, for instance membrane-assisted distillation, is another possible disruptive technology. This technology offers the possibility for the separations to occur at lower temperatures and also overcome limitation of individual separation process. However more RDD&D is still needed before hybrid separation process can be deployed in the industry.

Separation processes to reduce the energy consumed beyond BAT typically require customisation for process-specific approaches. A stakeholder consulted in this study estimated the long-term potential savings from disruptive separation technologies to be in the order of 25 - 75% of distillation energy. If challenges in advanced separation technologies can be overcome, there would be significant commercialisation opportunities and CO_2 abatement potential in the long term.

3.3 Chemicals Subsector

In terms of end-use, furnaces are the largest end-use of energy in the chemicals subsector, followed by the steam boilers and steam systems. Energy consumption in both these end-uses remains large even after the technical potential savings from BAT. Therefore, technologies related to furnaces and steam systems should be prioritised, as well as plant-wide or process specific technologies which will achieve significant savings in these end-uses. The following process types, as well as utilities, are the identified gaps to be targeted to achieve greatest overall impact in the subsector:

- System-Wide
- Distillation
- Steam Cracking

The technical potential estimates the level of energy savings and carbon dioxide abatement that would occur when all industrial processes, equipment and buildings are upgraded with EE measures that are technically feasible, regardless of any other constraints, such as cost and economic constraints. The economic potential estimates the level of savings that would occur if all current equipment/processes were replaced by best available technologies/practices (BAT) with positive net present values (NPV) at 2010. Together, BAT, emerging and next generation technologies have the technical potential to reduce the subsector's energy use by 12.9% by 2030 (Table 9).

- **Technical Potential:**
  - By 2030, chemicals subsector energy consumption could be reduced from the reference by:
    - 6.8% from currently available technologies and practices
    - 6.1% from emerging and next generation technologies and practices
  - By 2030, chemicals subsector CO_2 emissions could be reduced from the reference by:
    - 7.1% from currently available technologies and practices
    - 6.4% from emerging and next generation technologies and practices

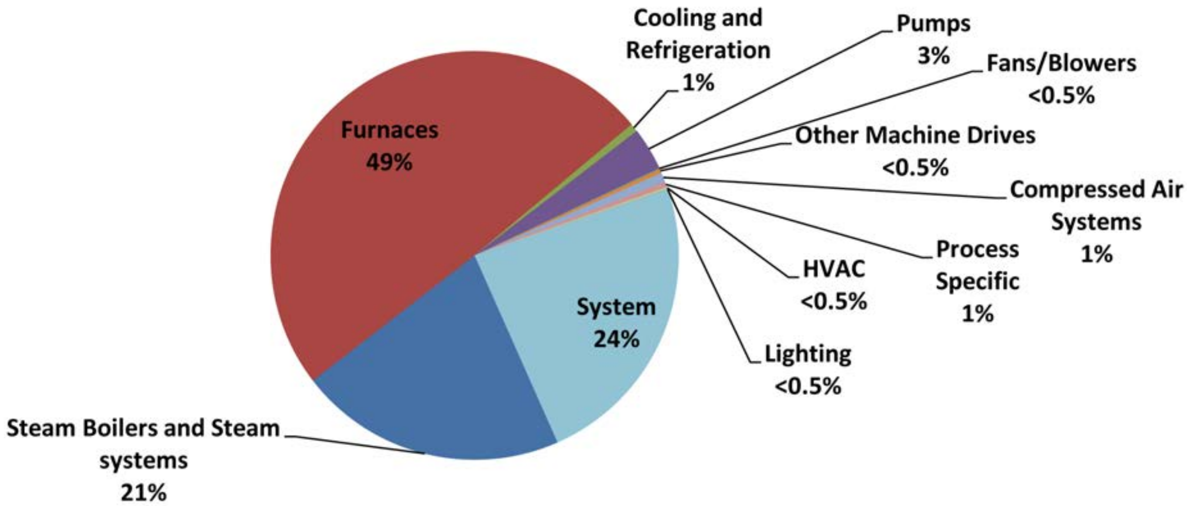
- **Economic Potential:**
  - By 2030, chemicals subsector energy consumption could be reduced from the reference by:
    - 5.3% from currently available technologies and practices
    - 6.0% from emerging and next generation technologies
  - By 2030, chemicals subsector CO_2 emissions could be reduced from the reference by:
    - 5.6% from currently available technologies
    - 6.3% from emerging and next generation technologies.

The largest potential is estimated to be for technologies that reduce the energy use at the system level for the entire plant , heating (boilers, steam systems and furnace end-uses), refinery and chemical plant integration, improved catalysts and super-critical CO_2 cycle heat recovery systems (Tables 9-11, Figure 17).

Table 9: Potential reduction in energy use by BAT and emerging / next generation technology within specific end-uses in 2030 (Chemicals subsector)

End-use	Technical Potential (%)		Economic Potential (%)	
	BAT	Emerging/NG Technologies	BAT	Emerging/NG Technologies
Steam boilers and steam systems	8.1%	0.7%	6.4%	0.5%
Furnaces	4.3%	6.0%	3.7%	6.0%
Cooling and refrigeration	13.8%	-	10.4%	-
Pumps	12.7%	-	12.3%	-
Fans/ blowers	3.2%	-	3.2%	-
Other machine drives	3.9%	-	2.9%	-
Compressed air systems	17.3%	-	15.4%	-
Process specific	6.8%	-	-	-
ACMV	15.4%	-	15.4%	-
Lighting	6.7%	-	5.0%	-
System	0.9%	2.1%	0.4%	2.1%
Co-Generation waste heat	-	-	-	-
Overall reduction in Chemicals energy use	6.8%	6.1%	5.3%	6.0%

Figure 17: Chemicals: 2030 technical potential energy savings



The technical potential savings that would occur if technologies were implemented are listed in Tables 10 and 11.

Table 10: Chemicals subsector top BAT opportunities (2030)

BAT	Technical Potential Savings (within subsector)	
	Energy	CO_2
Exhaust gas heat recovery (furnace)	1.1%	1.0%
Advanced distillation column	0.6%	0.6%
Waste heat recovery	0.4%	0.4%
Sub-metering and interval metering	0.4%	0.4%
Premium efficiency control with ASDs (pumps)	0.3%	0.5%

Table 11: Potential energy and emission savings by top emerging/ next generation technologies in 2030 (Chemicals subsector)

Emerging / Next Generation Technology	Technical Potential Savings (within subsector)	
	Energy	CO_2
Improved catalysts	3.7%	3.5%
Refinery and chemical plant integration	1.4%	1.3%
Super-critical CO_2 cycle heat recovery systems and other low grade waste heat recovery systems	0.8%	1.4%
Utility optimization through advanced control systems	0.2%	0.2%
Total reduction	6.1%	6.4%

3.3.1 Description of Selected New Technologies

Refinery and Chemical Plant Integration

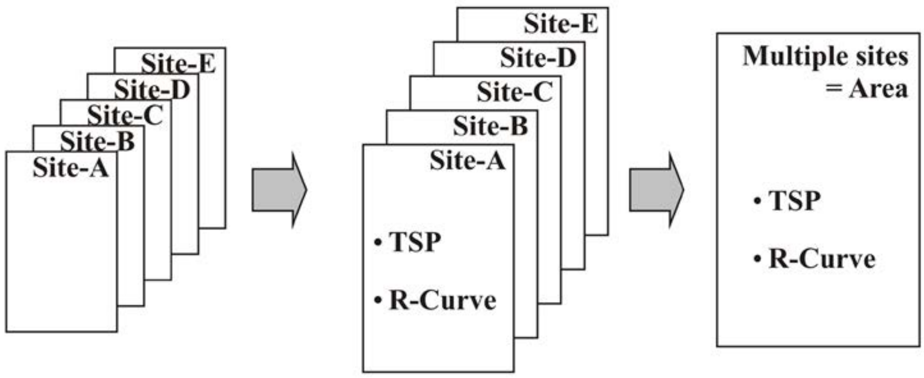
This measure involves efforts to further integrate separate chemical or refining facilities located in close proximity, such as on Jurong Island. Increased integration in the form of shared utilities can allow facilities to more efficiently and cost-effectively meet their respective process requirements. Certain resources are more practical to share between facilities, such as shared power, steam, cooling, and hydrogen. Inter-facility integration also could involve feedstock integration for chemical facilities which rely on refinery products, but such opportunities are more process specific and less broadly applicable than utilities integration.

This inter-plant integration measure is not necessarily limited to refineries and chemical plants, and could include integration with any other type of facility with significant utility requirements. The main constraint for a potential facility's applicability will be proximity, as utility sharing is less effective over large distances. Cogeneration facilities and possibly the LNG re-gasification facility would be of potential interest for integration.

To identify and validate opportunities for inter-plant integration, area-wide pinch technology is considered to be an appropriate methodology, by which an energy saving study of a whole industrial area can be undertaken. This allows more heat sources and sinks to be considered than when a single plant is considered individually, which can lead to a more efficient optimum balance. The first step to achieving inter-plant integration would be to use Area Wide Pinch Technology, consisting of total site profile (TSP) analyses and R-curve analyses of the facilities in question. Infrastructure would then need to be installed to allow for further utility sharing between facilities.

Figure 18 outlines the steps to complete an area-wide pinch study, starting by assessing plants individually and then considering them all as a single system.

Figure 18: Area-wide pinch analysis procedure (Matsuda, 2013)

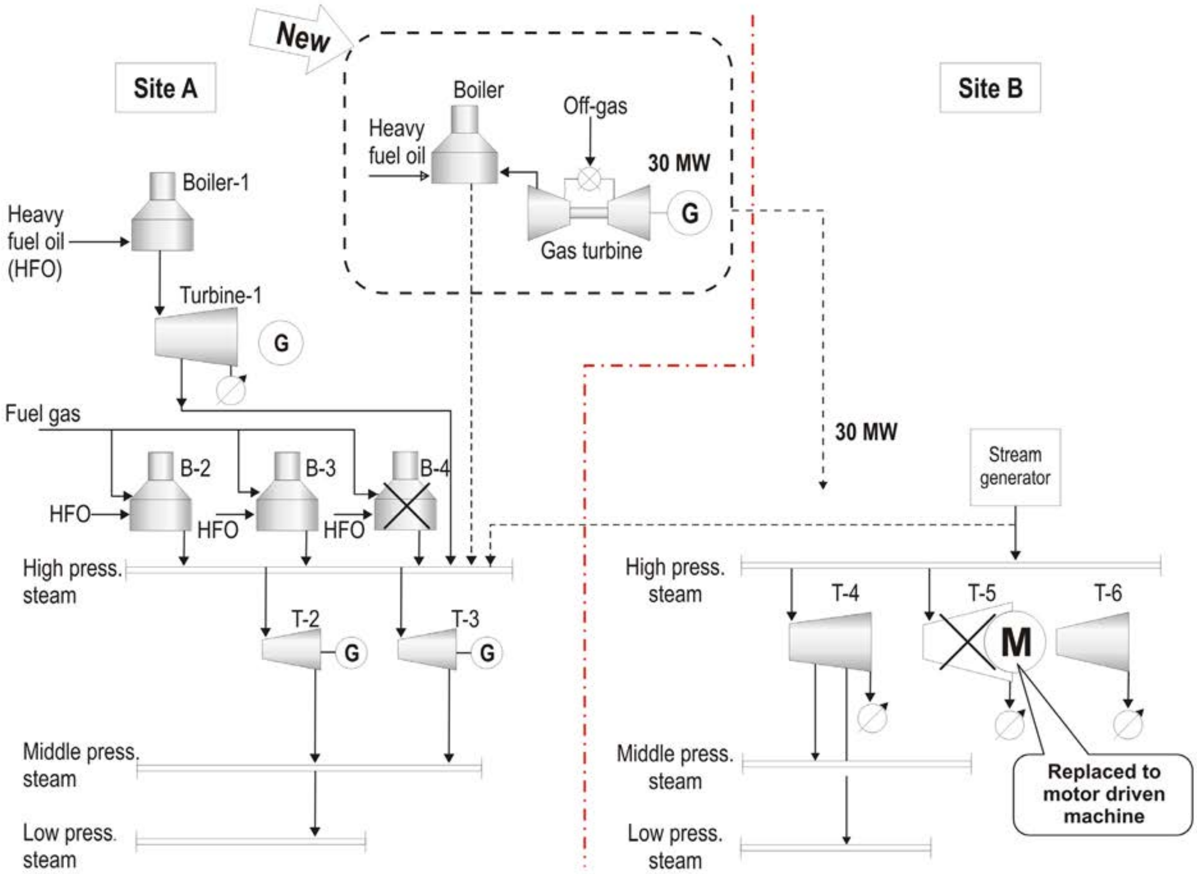


In TSP analysis, or Pinch analysis, data for individual process is used to develop composite curves, which are in turn combined to form a site heat source profile and a site sink profile. These two profiles form the total site profile (TSP), with one curve covering process heating exchangers, such as steam-heaters and reboilers, while the other curve covers process cooling exchangers, such as steam-generators, coolers and condensers. The R-curve analysis method is used to determine the most economical modifications to existing utility systems. For a given site power-to-heat ratio, the R-curve shows the maximum achievable efficiency, and provides a target for the efficiency of utility system. The difference between the existing efficiency and this maximum efficiency shows the potential for improvement (Matsuda, 2013).

It is therefore possible to find a large temperature difference between the heat supply side and the heat demand side. For example, low-grade heat (around 150–200 °C) of process streams is often chilled by coolers, and disposed of as waste heat. However, low-pressure steam (around 130 °C) could be produced from such heat. Middle-pressure steam (200–250°C) is sometimes used for reboilers, but it can be replaced with the lower pressure steam if the process stream requires low level heat (about 110°C) (Matsuda, 2013). This is just one example of how a pinch analysis can more efficiently match up heat sources and sinks to reduce the systems' overall energy consumption.

In addition to balancing heat sources and sinks, the increased scale and common utility requirements of integrated facilities can create opportunities to share utility generation equipment with other sites and increase operational flexibility. Figure 19 demonstrates an energy sharing system developed for a refinery and a chemical plant to integrate and reduce their energy consumption.

Figure 19: Example of energy sharing system possible through multi-plant integration (Matsuda, 2013)



The refinery (Site A in Figure 19) was able to replace an inefficient and unreliable high-pressure steam boiler, partially through high-pressure steam (dotted lines) supplied by the chemical facility (Site B) and partly through a newly constructed combined heat and power (CHP) unit. To free up high-pressure steam, the chemical facility replaced one condensing turbine with a more efficient motor, which was powered by electricity from the same CHP system (dashed lines). In this application, the energy savings were not possible without the integration of both facilities.

Some other specific potential opportunities that are present in Singapore include:

- Further integration of co-gen plants with surrounding facilities. This could include ensuring that steam from cogen plant is optimised to match the heating requirements of surrounding plants, more distribution of heating loops so that small facilities not capable of installing co-gen can still reap some benefits, and possibly adjusting power to steam production ratios based on time of day requirements.
- Integration to allow some facilities to get more use of excess steam production (and incentivising them to meet heating demands with waste heat wherever possible), while at the same time allowing another facility to avoid burning fuel to produce temperatures that are in excess supply at nearby plants.

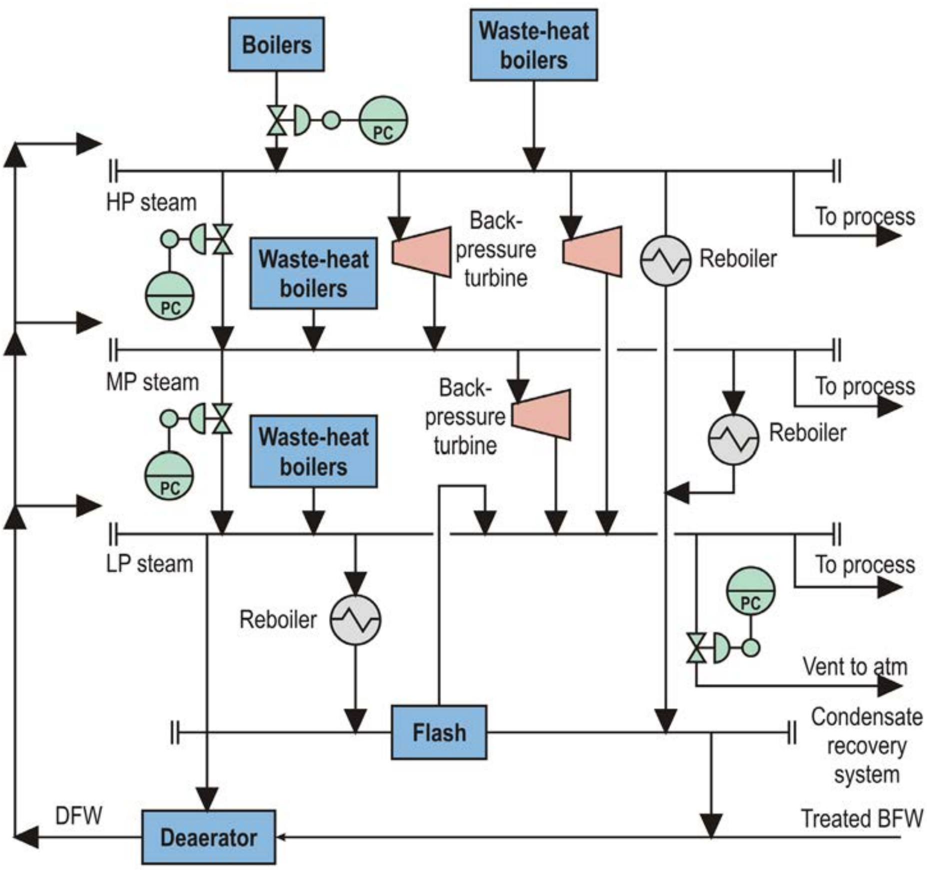
- Avoiding inefficient uses of excess plant hydrogen, which can be treated and sold to meet a different plant's requirements.
- Chilled water cooling loop from LNG re-gasification import terminal.

In Singapore, many chemical plants and petroleum refineries are located in relatively close proximity, with such facilities concentrated on Jurong Island and surrounding areas. This close proximity opens up opportunities for integration between plants which might not be possible elsewhere, and can potentially be leveraged to provide a competitive edge to facilities in Singapore. The presence of significant amounts of cogeneration and a LNG re-gasification system also present potential opportunities for energy savings through integration.

Utility Optimisation through Advanced Control Systems

The importance of control systems to assist operators to run their plants more efficiently is demonstrated in Figure 20. This simplified representation of a chemical plant steam system highlights some of the components operators balance to meet their facility's energy requirements. Such a system can meet these requirements through many different combinations of equipment operation, but certain combinations will be more efficient, and the optimal combination can change over time. Generally speaking, the more complex and variable the system, the more difficult it is for operators to keep the utility systems operating optimally. A key means to improve efficiency is to minimise or eliminate letdown of steam and maximise letdown across reboilers or turbines so as to extract useable energy. This measure represents control systems that enable plant operators to achieve more energy efficient operating conditions.

Figure 20: Basic elements of a chemical plant steam system (Pelham, 2013)



This measure applies to all the utility systems at the plant, and the end-uses within them. This includes the systems controlling the production and use of steam, fuel, waste heat, cooling, electricity, and co-generation. All of this utility equipment, and its energy requirements, need to be balanced together when trying to achieve the most efficient plant operation possible.

Power and steam systems in chemical plants are complex groupings of equipment and processes, including cogeneration of power and steam, steam production from fired boilers, and steam headers with different pressures. Improving energy efficiency in chemical plants by using extraction turbines for steam letdown or dual-drive equipment (steam or electricity options) will further increase the complexity. This combined with the dynamic nature of process operations means it is generally beyond the ability of operators to constantly adjust set points to optimize the energy efficiency.

The use of utility optimisation system is required to assist in the optimisation of energy efficiency. Utility optimisation systems that consist of energy, mass, and cost (of energy) balance models of the utility systems can continuously determine this most efficient combination in order for ongoing adjustments to ensure that the plant operates at minimum total energy consumption. The crux of the issue is that while the answer to isolated decisions might seem obvious, it is difficult for operators to come up with the most efficient operational combinations when balancing many variables in real time. Advanced controls can also help optimise migration between operating modes or ramping up or down of utility production, which will likely be done in a sub-optimal way without the help of such systems.

In addition to the real-time optimisation functions, such systems can be used to establish energy performance metrics, for which goals can be set and progress monitored. These metrics are often called Key Performance Indicators (KPI's) and could include:

- **High level KPI's** that monitor overall site performance and are geared toward use by site and corporate management. For example: Total cost of the utility systems, predicted benefits, main steam headers imbalances, emissions, etc. (Ruiz, 2011a).
- **Unit level KPI's** that monitor individual unit performance and are geared toward use by unit management and technical specialists. For example: plant or area costs, boilers and heaters efficiencies, etc. (Ruiz, 2011a).

A more general Key Performance Indicator (KPI) was established to track the implementation of this emerging measure. This KPI is the energy consumption of utilities as a percentage above the optimised minimum. Ideally, plants would operate at this optimised level, while in reality plants without such control systems typically operate above this level of minimum energy requirements. Stakeholder feedback indicated that typical current performance levels of steam and power systems in Singapore result in a total energy consumption that is 2-5% above the minimum achievable with optimised loading of utilities producers and consumers. This would correspond to plant operators maximising system performance based on experience.

While utility optimisation control systems to improve plant performance are available on the market, and could already be considered BAT, the adoption in Singapore is low. As advanced control system offerings continue to be improved by technology vendors, including more specialised and plant specific models, as well as added features such as equipment monitoring for predictive maintenance, it is a priority to encourage deployment of such technologies.

While local KPI's within a facility can be useful, too often different business groups end up hurting the overall plant performance by improving their own metrics at the expense of other groups. For this reason, global plant wide KPIs are recommended to describe and track plants. These could include overall energy intensity, product yield on a material basis, or product yield on a cost basis. Advanced control systems are well aligned for such plant wide KPIs, and are able to consider a wide range of variables to track these indicators.

Control systems to aid with utility optimisation become even more important as integration and utility sharing between neighboring facilities increases, since such arrangements increase the variables that can be controlled to maximise overall plant efficiency (Ruiz, 2011b).

Increased deployment of advanced control systems for utility optimisation can achieve significant energy savings for the chemical facilities in Singapore by enabling them to be more efficient in their energy consumption. This measure applies broadly throughout the subsector, is well aligned with other industry priorities (increased reliability, safety, etc.), and can help offset the impact of high energy prices on the industry in Singapore. Stakeholders identified that it is often difficult for facilities to adjust their main processes, and that as a result utilities should be a priority target area for energy efficiency improvements in the chemical industry. Such utility optimisation systems are also applicable in refineries and other industries which have complex utility systems.

3.4 Semiconductor Subsector

In terms of end-uses, air-conditioning and mechanical ventilation (ACMV) is the largest consumer of energy in this subsector, followed by the process specific end-use. Energy consumption in both these end-uses remains large even with BAT. It should be noted that technologies related to ACMV and other utilities likely offer greater opportunity for improvement by advanced technologies, than process equipment in this industry. This is because ACMV equipment are generic and consistent across all facilities within the semiconductor manufacturing sector. In addition, building ACMV is a base load that does not really fluctuate based on the productivity of a facility, making it a more predictable opportunity. Within each plant there are many different types of process specific equipment, and different plants will use different processes and hence different equipment.

The technical potential estimates the level of energy savings and carbon dioxide abatement that would occur when all industrial processes, equipment and buildings are upgraded with EE measures that are technically feasible, regardless of any other constraints, such as cost and economic constraints. The economic potential estimates the level of savings that would occur if all current equipment/processes were replaced by best available technologies/practices (BAT) with positive net present values (NPV) at 2010. Together, BAT, emerging and next generation technologies have the technical potential to reduce the subsector's energy use by 33.1% by 2030 (Table 12).

- **Technical Potential:**
  - By 2030, subsector-wide energy consumption could be reduced from the reference by:
    - 21.1% from currently available technologies and practices
    - 12.0% from emerging and next generation technologies and practices

- By 2030, subsector-wide CO_2 emissions could be reduced from the reference by:
  - 21.5% from currently available technologies and practices
  - 12.3% from emerging and next generation technologies and practices

- Under the **Economic Potential:**
  - By 2030, subsector-wide energy consumption could be reduced from the reference by:
    - 20.7% from currently available technologies and practices
    - 11.6% from emerging and next generation technologies and practices

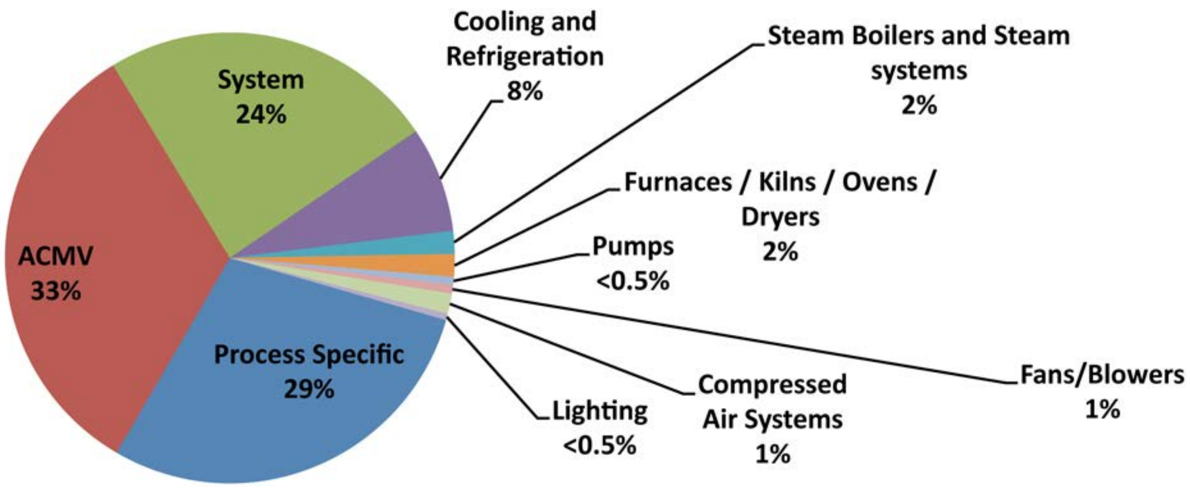
  - By 2030, subsector-wide CO_2 emissions could be reduced from the reference by:
    - 21.2% from currently available technologies and practices
    - 11.9% from emerging and next generation technologies and practices

The largest potential is estimated to be for technologies that reduce the energy use at the systems level for the entire plant and to reduce energy use in the process specific end-use, such as advanced product and process control and ultra-pure water generation technology (reverse osmosis with electro-deionisation) (Tables 12 to 14, and Figure 21).

Table 12: Potential reduction in energy use by BAT and emerging / next generation technology within specific end-uses in 2030 (Semiconductor subsector)

End-use	Technical Potential (%)		Economic Potential (%)	
	BAT	Emerging/NG Technologies	BAT	Emerging/NG Technologies
Steam boilers and steam systems	8.6%	-	8.6%	-
Furnaces / kilns / ovens / dryers	-	13.0%	-	13.0%
Cooling and refrigeration	21.5%	4.2%	20.8%	-
Pumps	8.5%	-	8.5%	-
Fans/blowers	3.9%	-	3.4%	-
Other machine drives	-	-	-	-
Compressed air systems	9.1%	-	7.5%	-
Process specific	12.1%	21.2%	12.1%	21.2%
ACMV	31.9%	-	31.9%	-
Lighting	19.0%	-	19.0%	-
Other	-	-	-	-
System	3.1%	4.9%	2.9%	4.9%
Overall reduction in Semiconductor energy use	21.1%	12.0%	20.7%	11.6%

Figure 21: Semiconductor: 2030 technical potential energy savings



The technical potential savings that would occur if technologies were implemented are listed in Tables 13 and 14.

Table 13: Semiconductor subsector Top BAT Opportunities (2030)

BAT	Technical Potential Savings (within subsector)	
	Energy	CO_2
High efficiency non-packaged ACMV equipment	5.0%	5.1%
Load lock green mode pumps	3.5%	3.5%
Ventilation heat recovery	3.0%	3.0%
Demand-controlled ventilation	2.0%	2.0%
Sub-metering and interval metering	1.9%	1.9%

Table 14: Potential energy and emission savings by top emerging/ next generation technologies in 2030 (Semiconductor subsector)

Emerging / Next Generation Technology	Technical Potential Savings (within subsector)	
	Energy	CO_2
Advanced product and process control	4.9%	5.1%
Ultra-pure water generation technology (Reverse osmosis with electro-deionisation)	4.5%	4.6%
Super high efficiency nitrogen plant	1.6%	1.6%
Furnace vacuum Insulation	0.5%	0.6%
Triple-effect absorption chillers	0.3%	0.3%
Ultra-efficient chillers/magnetic-bearing chillers	0.1%	0.1%
Total reduction	12.0%	12.3%

3.4.1 Description of Selected New Technologies

Ultra-pure Water Generation Technology

Semiconductor manufacturers require large volumes of ultrapure water to rinse impurities from wafer surfaces. The purity requirements continue to be more and more stringent over time, as do the desire to achieve water and energy savings through efficiency gains. Reverse osmosis (RO) is often considered the workhorse of the ultra-pure water (UPW) generation process, as it is the technology that removes the bulk of the impurities. Understanding exact energy savings from this reverse osmosis (RO) technology is complex, with salinity, temperature, pH, scaling tendency, fouling index and ionic content all requiring consideration. Pre-heating the water reduces osmotic pressure, which increases the deionisation process efficiency. RO has traditionally been paired with ion exchange technology, but improvements to electro-deionisation (EDI) yield important advantages, including low energy consumption, no chemical requirement, regeneration of resins, and lower operating costs. EDI uses a stack of alternating anion and cation exchange membranes. In between the ion exchange membranes, mixed bed resins are present, necessary for continuous regeneration. An electric current drives the ions, captured by the ion exchange resins through the membrane. Water is ionised by the electric current, which enable constant regeneration of the ion exchange resin inside the module. Therefore, the resin does not become depleted and there is no need for chemical regeneration or downtime (Fuji, 2011).

Advanced Product and Process Control

Advanced product and process control focuses on improving process controls to achieve productivity and other benefits. Recently it has been recognised that proactive product quality control must be coordinated with process control. A multi scale scheme has been proposed, containing 3 layers for coordinated equipment control, process control and product quality control (Liang, 2011). The overall equipment effectiveness (OEE) and the overall product performance (OPP) are enhanced through individual control of equipment and the use of an exponentially weighted moving average (EWMA) run-to-run controller to prevent reoccurrences of product quality problems. The potential model predicts that 8% electricity savings will result from the application of integrated control systems. It is estimated that additional savings could be achieved through subsector specific research in integrated product and process control research. In addition, making use of modular clean rooms can add to the savings.

There are also opportunities to improve upon current EDI technology, such as through fractional electrodeionisation (a new patented technology) or membrane-free electrodionisation (Su et al. 2013).

Super High Efficiency Nitrogen Plant

Semiconductor manufacturing uses large volumes of liquid nitrogen for cryogenic uses and nitrogen gas for atmospheric control. The two main methods for producing nitrogen include cryogenic production and adsorption; the energy use per unit of nitrogen is similar for both processes (0.25-3 kWh/nm^3 and 0.3-0.4 kWh/nm^3, respectively) (Carbon Trust, 2011).

The International SEMATECH Manufacturing Initiative (ISMI) identified nitrogen system efficiency and clean dry air (CDA) efficiency as two of the priority focus areas to further enable effective energy savings in the subsector (Silicon Semiconductor, June 2012). CDA is compressed, oil free, de-watered and filtered air that is produced using a single compression process. It can be used to substitute nitrogen in application where inert conditions are not required. Technologies that have emerged in recent years that have improved the energy efficiency of CDA generation include enhanced membrane materials and compressor off-loading.

3.5 Pharmaceutical Subsector

The energy efficiency opportunities below were identified for further investigation:

- **Thermal generatio**n, which includes steam generation used for both ACMV and process requirements.
- **Chilled water**, which includes chillers and cooling water for ACMV requirements.
- **Cooling tower water.**
- **Low Temperature Chillers (LTC)**, which includes the electricity used by both low-temperature chillers and the pumps that are part of process cooling systems.
- **Process equipment.** Equipment improvements could also reduce energy in previously listed areas, such as LTC and thermal generation, they could also lower process specific electricity use (pumps), and other process utilities like compressed air, nitrogen, etc. This may include continuous processing and reducing waste. Greatest efficiencies can be achieved through an integrated facility design process. Efficiencies are generally smaller and more difficult to obtain once the initial design has been established.

Technologies related to ACMV and other utilities likely offer greater opportunity for improvement by advanced technologies than process equipment in this industry. This is because ACMV equipment will be more consistent across all facilities within the pharmaceutical manufacturing sector. Within each plant there are many different types of process specific equipment, and different plants will use different processes and hence different equipment. In addition, building ACMV is a base load that does not really fluctuate based on the productivity of a facility, making it a more predictable opportunity. A major challenge to the adoption of new process technologies in the pharmaceutical subsector is the strict regulation of products by authorities such as the United States Food and Drug Administration. Thus new technologies will have to undergo rigorous testing to prove that the safety and quality of the products are not altered with the use of new processes.

The technical potential estimates the level of energy savings and carbon dioxide abatement that would occur when all industrial processes, equipment and buildings are upgraded with EE measures that are technically feasible, regardless of any other constraints, such as cost and economic constraints. The economic potential estimates the level of savings that would occur if all current equipment and processes were replaced by best available technologies and practices (BAT) with positive net present values (NPV) at 2010. Together, technologies have the technical potential to reduce the subsector's energy use by 23.5% by 2030 (Table 15).

- **Technical Potential:**
  - By 2030, subsector-wide energy consumption could be reduced from the reference by:
    - 21.1% from currently available technologies and practices
    - 2.4% from emerging and next generation technologies and practices
  - By 2030, subsector-wide CO_2e emissions could be reduced from the reference by:
    - 22.9% from currently available technologies and practices
    - 3.2% from emerging and next generation technologies and practices
- **Economic Potential:**
  - By 2030, subsector-wide energy consumption could be reduced from the reference by:
    - 20.6% from currently available technologies and practices
    - 2.2% from emerging and next generation technologies and practices

- By 2030, subsector-wide CO_2e emissions could be reduced from the reference by:
  - 22.5% from currently available technologies and practices
  - 3.0% from emerging and next generation technologies and practices.

The largest potential is estimated to be for technologies that reduces the energy use at the systems level for the entire plant and to reduce energy use in the process specific end-use, such as advanced facility automation, green chemistry and multi-step synthesis in one pot (Tables 15 to 17, and Figure 22).

Table 15: Potential reduction in energy use by BAT and emerging / next generation technology within specific End-uses in 2030 (Pharmaceutical subsector)

End-use	Technical Potential (%)		Economic Potential (%)	
	BAT	Emerging/NG Technologies	BAT	Emerging/NG Technologies
Steam boilers and steam systems	17.0%	-	16.4%	-
Cooling and refrigeration	20.8%	-	20.6%	-
Pumps	11.8%	-	11.8%	-
Fans/blowers	5.9%	-	5.9%	-
Other machine drives	11.8%	-	11.8%	-
Compressed air systems	16.7%	-	16.7%	-
Process specific	14.1%	15.3%	14.1%	14.1%
ACMV	34.7%	1.7%	34.7%	-
Lighting	26.6%	-	26.6%	-
Other	-	-	-	-
System	1.8%	1.4%	1.8%	1.4%
Co-generation waste heat	-	-	-	-
Overall reduction in Pharmaceutical energy use	21.1%	2.4%	20.6%	2.2%

Figure 22: Pharmaceutical– 2030 technical potential energy savings

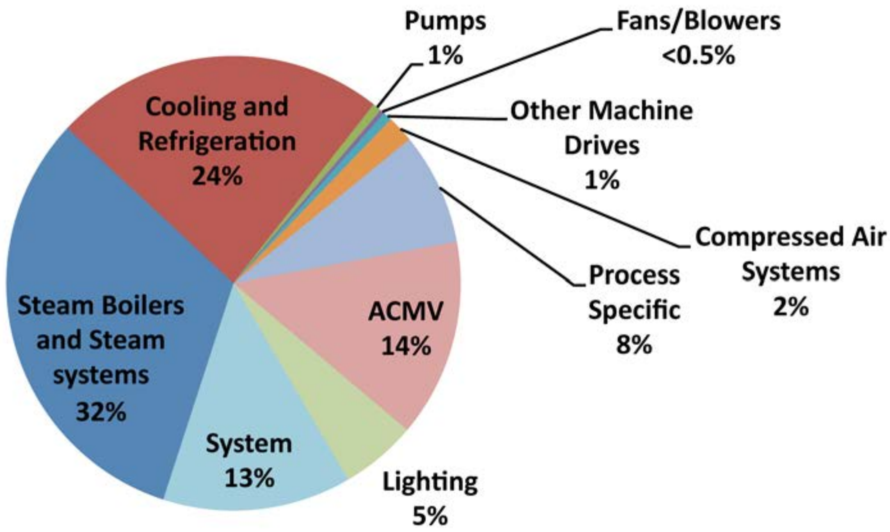


Table 16: Pharmaceutical subsector top BAT opportunities (2030)

BAT	Technical Potential Savings (within subsector)	
	Energy	CO_2
Variable speed drive on chiller compressor	4.1%	5.0%
Boiler right sizing	2.1%	1.3%
Sub-metering and interval metering	1.7%	1.7%
Flue gas monitoring (boiler)	1.2%	1.6%
High efficiency chiller	1.1%	1.3%

Table 17: Potential energy and emission savings by top emerging/ next generation technologies in 2030 (Pharmaceutical subsector)

Emerging / Next Generation Technology	Technical Potential Savings (within subsector)	
	Energy	CO_2
Advanced facility automation	1.4%	1.8%
Green chemistry	0.5%	0.6%
Multi-step synthesis in one pot	0.2%	0.3%
Continuous processing equipment	0.2%	0.3%
Optimize make up air unit design for cleanroom ACMV system	0.2%	0.2%
Process analytical technology (PAT)	0.1%	0.1%
Total reduction	2.4%	3.2%

3.5.1 Description of Selected New Technologies

Green Chemistry

Green chemistry (as defined by the U.S. EPA) efficiently utilises (preferably renewable) raw materials, eliminates waste, and avoids the use of toxic, hazardous reagents and solvents in the manufacture and application of chemical products (Dunn et. al., 2010).

Green chemistry involves shifting from organic chemical synthesis to enzyme-catalysed biological synthesis, which is less energy intensive. Biocatalysis involves mimicking equivalent processes in nature, where water is used as the solvent (rather than large quantities of solvents and reactive reagents) and synthesis is carried out at room temperature (PM Group, 2011). One example of a process that can be adapted in this way is distillation. One stakeholder suggested that green chemistry should also include Bio-Enzymatics, where biological catalysts, enzymes, are used to convert either biological or chemical feedstock into useful products.

One of the 12 green chemistry principles that relates most directly to energy is “design for energy efficiency” and relates to shortening processes and operating at milder conditions (ambient temperature and pressure) when possible.

The environmental factor (E factor) is an accepted metric used by the industry to measure the environmental footprint of manufacturing processes and is equal to the kilograms of waste per kilogram of desired product. The ideal E factor is zero. The KPI for the emerging technology is 5-50 E factor as compared to 25-100 E factor for BAT (Dunn et. al., 2010).

Advanced Facility Automation

This improvement includes advanced monitoring and controls of both production and building systems. This allows superior management of utilities by optimising operation and performance of fans, pumps, and compressors as needed. For example, Siemens’ Power Management System optimises the use of energy and achieves reductions in energy costs by up to 20% (Siemens, 2010). The technologies themselves are mature, and it is quite often more a question of application and a commitment to energy efficiency.

Multi-step Synthesis in One Pot

Pharmaceutical manufacturing often involves complex multi-step synthesis which requires expensive isolation and purification of intermediates and generates a large amount of waste. An economic and sustainable solution is to perform multi-step reactions in one pot. In addition to chemical approaches, enzymatic reactions, which are non-toxic and often highly selective, have similar reaction conditions and thus can be performed in one pot. Multiple enzymes expressed in microbial cells or immobilised on solid carrier can be efficient catalysts for one-pot multi-step reactions. Researchers in Singapore are already making strides in this area (Yu et. al., 2013). The evolution of the industrial process route for the synthesis of the antibiotic cephalexin (to a 2-step process) resulted in a 40% reduction in energy consumption (Schoevaart and Kieboom, 2001).

3.6 Generic Technologies

Generic technologies refer to those technologies that apply across all industrial subsectors. Some end-uses, such as pumps, fans, and compressed air systems, are mainly cross-cutting end-uses and include only generic technologies, while other end-uses, such as furnaces and steam systems also include both generic technologies and process specific technologies. Apart from technologies identified for specific subsectors, additional generic technologies that have high potential for reducing the energy consumption of multiple subsectors were identified (Table 18). The top additional emerging and next generation technologies are:
Advanced process heater
Smart Manufacturing / Advanced Facility Automation
Large scale solar thermal system

Table 18: Potential energy and emission savings by additional generic emerging/ next generation technologies in 2030

Emerging / Next generation Technology	Total Technical Potential Savings (within entire industry sector)	
	Energy	CO_2
Advanced process heater	0.44%	0.57%
Smart Manufacturing / advanced facility automation		
Large scale solar thermal system		

3.6.1 Description of Selected New Technologies

Smart Manufacturing / Advanced Facility Automation

Intelligent efficiency approach offers businesses and manufacturers the ability to save energy as well as provide a mechanism for greater efficiency and productivity. Energy saving is achieved not only at the device level but at the system level and above. Intelligent efficiency goes beyond devices and uses a systems level approach by connecting standalone devices and taking into account the purpose or goal of the system by optimising the behavior of the system's components relative to one another to achieve that goal (Rogers et. al. 2013). As a system approach, intelligent efficiency involves integrating the performance of a suite of individual technologies to function as a network utilising information and communication technology and real-time information (Rogers et. al. 2013). The more connected the components are, the more powerful the network will be.

In the manufacturing sector, the networking of devices such as machine to machine creates capability called smart manufacturing. This intelligent efficiency based process design connects facility operations to corporate enterprise management. The corporate system will also be linked with other systems along the supply chain. Smart manufacturing technologies control system minimises energy use, water use, and emissions through optimised operations and by predicting bottlenecks and breakdowns in the factory. Smart manufacturing technologies have been incorporated in Rockwell Automation's new automobile manufacturing facility (Elliot, 2012).

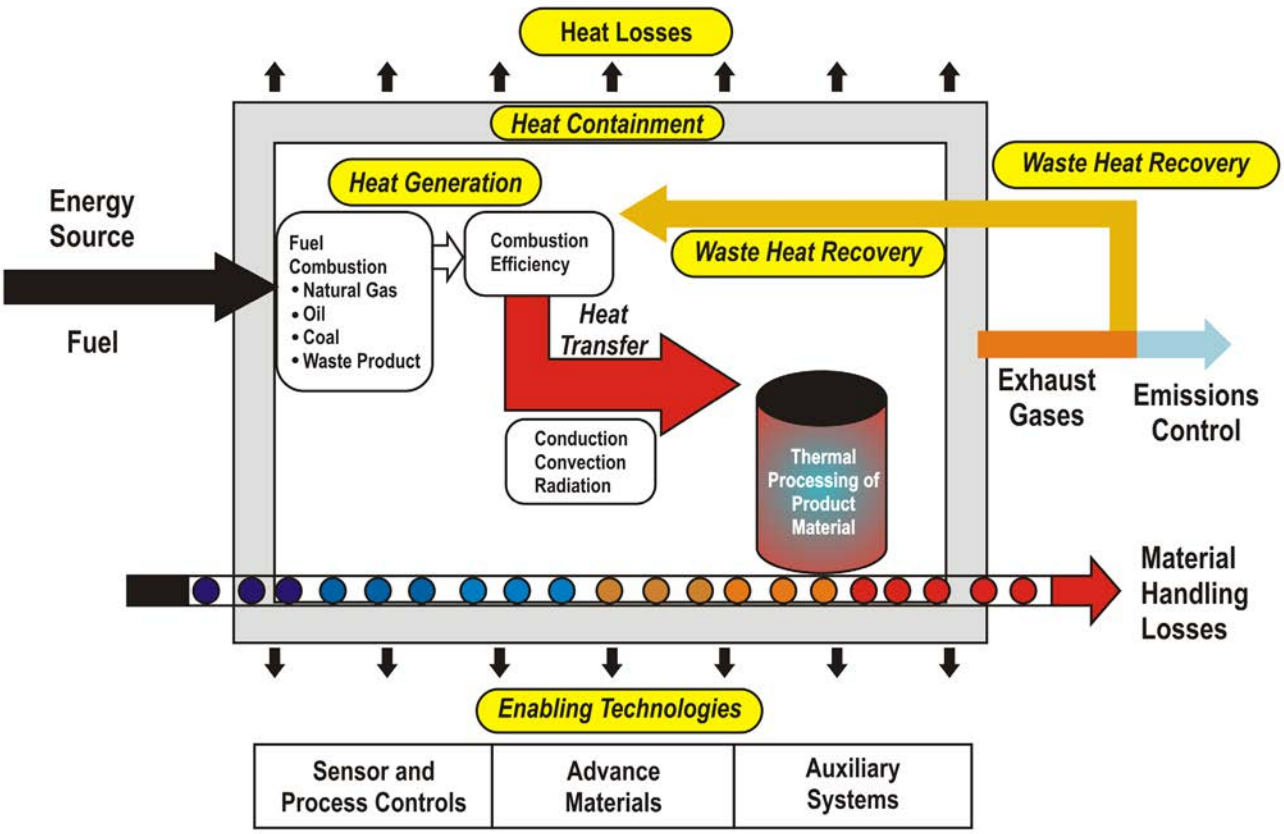
Advanced facility automation allows for greater decision making for efficiency at the facility by utilising advanced algorithms to control components and processes hence increasing the connectivity of the components by the use of a third party software that manages the different component of the entire operation from the supplier to the customer. Advanced facility automation provides a monitoring system that collects real-time and non-real time information that can be analysed to allow third party software to make decisions to improve the efficiency through the integration of computer aided facility management information systems and automation systems (Rogers et. al. 2013).

Advanced Process Heaters

Process heating is required in the manufacture of most consumer and industrial products. Fuel-based systems generate heat through the combustion of fuel, which is then transferred either directly or indirectly for process heating. Energy efficiency of a process heating system is determined by the costs attributable to the heating system per unit of product. There are several energy losses in a fuel-based process heating systems; flue losses, wall loss, opening loss, conveyor loss, and cooling water loss. Therefore the main goals of performance optimisation are reduced energy losses and increased energy efficiencies (US Department of Energy, 2007).

Advanced process heater systems aim to attain performance and efficiency improvements in five areas (Figure 23); heat generation, heat containment, waste heat recovery, heat transfer and enabling technologies (US Department of Energy, 2007).

Figure 23: Energy losses and improvement opportunities in a fuel-based process heating system (U.S. Department of Energy, 2007)

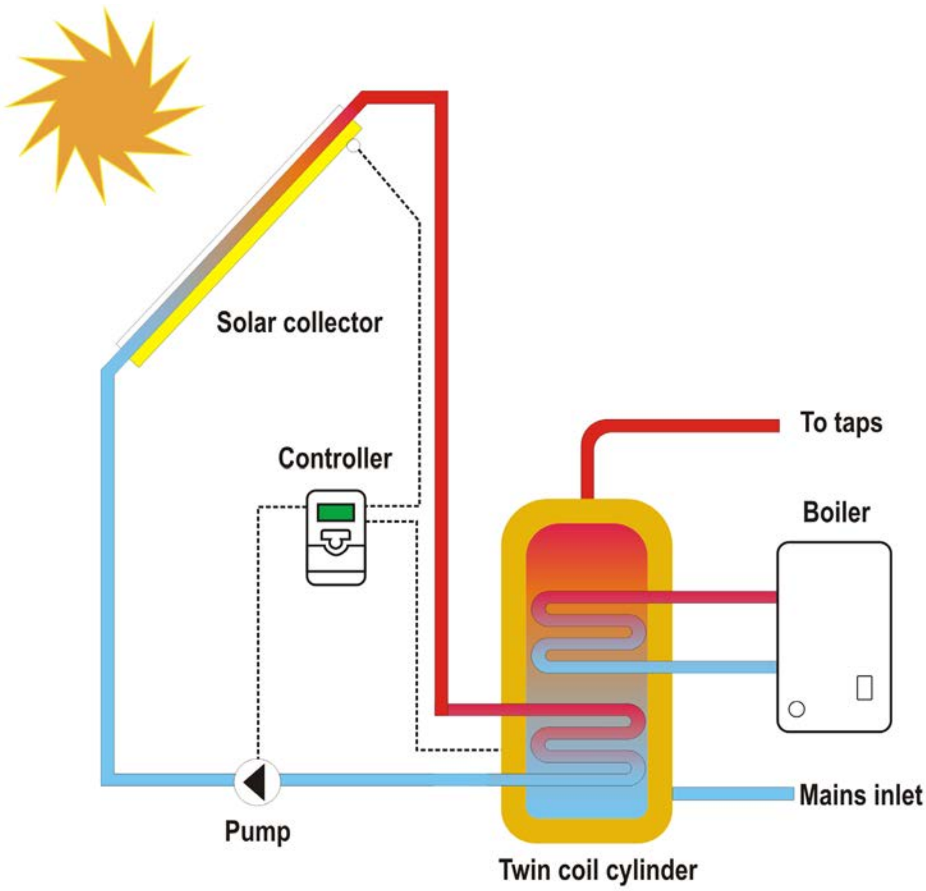


Large Scale Solar Thermal System

Solar thermal systems involve the conversion of solar energy into useful heat. The systems are designed to absorb solar radiation for thermal energy (heat) requirements in residential, commercial and industrial applications. Large Scale Solar Thermal systems can be suitable to meet the process heating needs of a variety of industrial sectors (Vannoni et. al., 2008; Stryi-Hipp, G. et al., 2008).

Pumps or fans are used to transfer the heat from the solar collectors to storage or for distribution directly to its intended use. The pump detects the temperature difference between the solar collector and the storage tank. When the temperature in the collector is lower than the temperature in the tank, the system remains on standby. When the temperature in the collector is above the temperature in the tank, the pump is activated and the solution is circulated through the solar collector (Figure 24).

Figure 24: Simplified solar thermal system (eCO_2solar)



Some of the research and development goals for the non-residential sector include: developing dedicated medium and high temperature collectors, developing cost competitive turn-key solar thermal process heat systems, developing solar thermal energy based poly-generation systems, and developing advanced large-scale solar thermal district cooling and heating systems.

4 Challenges and Barriers

The technical and market risks were assessed for the selected emerging and next generation technologies specific to the Singapore context. These risks are summarized in Table 19 as it pertains to specific technologies, and the risks include the following:

- Complexity of targeted processes
- Impact on process unknown
- Unproven technology
- Perception that process(es) are already optimised
- High initial investment
- Unattractive ROI
- Increased inter-organisational collaborations required
- RDD&D organisational alignment needed
- Limited financing for RDD&D
- Competing RDD&D investments
- Require substantial changes to existing plant infrastructure Limited application expertise
- Limited O&M support in region
- Low potential for scalability in Singapore

Table 19: Selected emerging / next generation technologies representing major energy intensive subsectors: Risks and follow-up actions

Technology Name	Subsector	Technical and Market Risks	Possible Follow-up Actions
Improved catalysts	Refining and chemicals	• Impact on process unknown • RDD&D organisational alignment needed • High initial investment	• Research programs • International collaborations • Alternative financing schemes
Refinery and chemical plant integration	Refining and chemicals	• Increased inter-organisational collaborations needed • Unfavorable policies / regulations • Impact on process unknown	• Technology RDD&D centers • New shared risk framework • Demonstrations
Super-critical CO_2 cycle heat recovery systems	Refining and chemicals	• Unproven technology • Complexity of targeted processes • Limited financing for RDD&D	• Research programs • International collaborations • Demonstrations
Smart Manufacturing / advanced facility automation	Generic (All)	• Require substantial changes to existing plant infrastructure Impact on process unknown • Limited application expertise in Singapore • High initial investment	• Financial incentives • Industry collaboration and investment • Share case studies and best practices

Technology Name	Subsector	Technical and Market Risks	Possible Follow-up Actions
Ultra-pure water generation technology (Reverse osmosis with electro-deionisation)	Semi-conductor	• Unproven technology • Unattractive ROI / high investment • Uncertainty about economic stability	• Research programs • International collaborations • Financial incentives
Advanced process heater	Generic (All)	• Unproven technology • Unattractive ROI / high investment • Require substantial changes to existing plant infrastructure	• Technology deployment programs • Alternative financing schemes • Case studies and share best practices
Utility optimisation through advanced control systems	Chemicals	• Impact on process unknown • High initial investment • Perception that utilities already optimized	• Technology deployment programmes • Alternative Financing schemes • Share best practices and case studieses
Super high efficiency nitrogen plant	Semi-conductor	• Technical barriers yet to be overcome Competing RD-D&D priorities • Small potential scalability in market	• Research programs • International collaborations • Financial incentives

5 Conclusion

5.1 Recommendations

Bridging the 'Valley of Death'

The gap ('valley of death') between government and university investments in basic research (concentrated at low TRLs) and private sector investments in commercialisation (concentrated at high TRLs) needs to be bridged. Approaches developed by New York State Energy and Research and Development Authority (NYSERDA) and US Department of Energy (US DOE) to bridge this gap are illustrated in Figure 25 and Figure 26.

The US DOE Advanced Manufacturing Office (AMO) is aiming to establish 8 Clean Energy Manufacturing Innovation Institutes to demonstrate advanced materials and processes technologies, leading to commercialization. These centers are part of a strategy to address the "valley of death" in the RDD&D spectrum, as it has been identified that there is a funding gap.

Figure 25: NYSERDA's approach to energy efficiency RDD&D (NYSERDA, 2013)

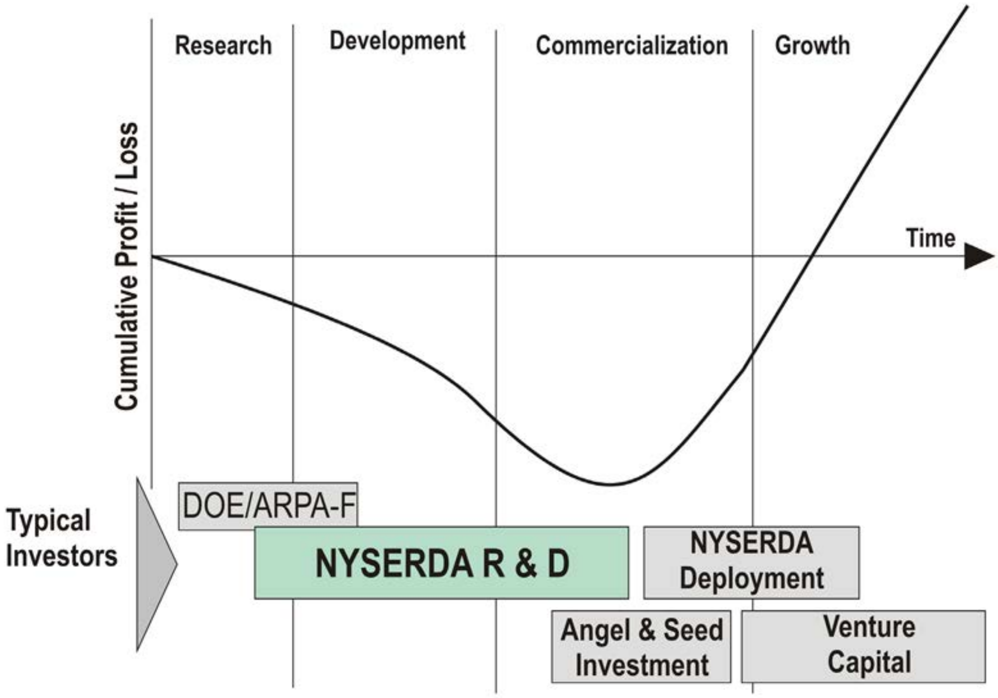
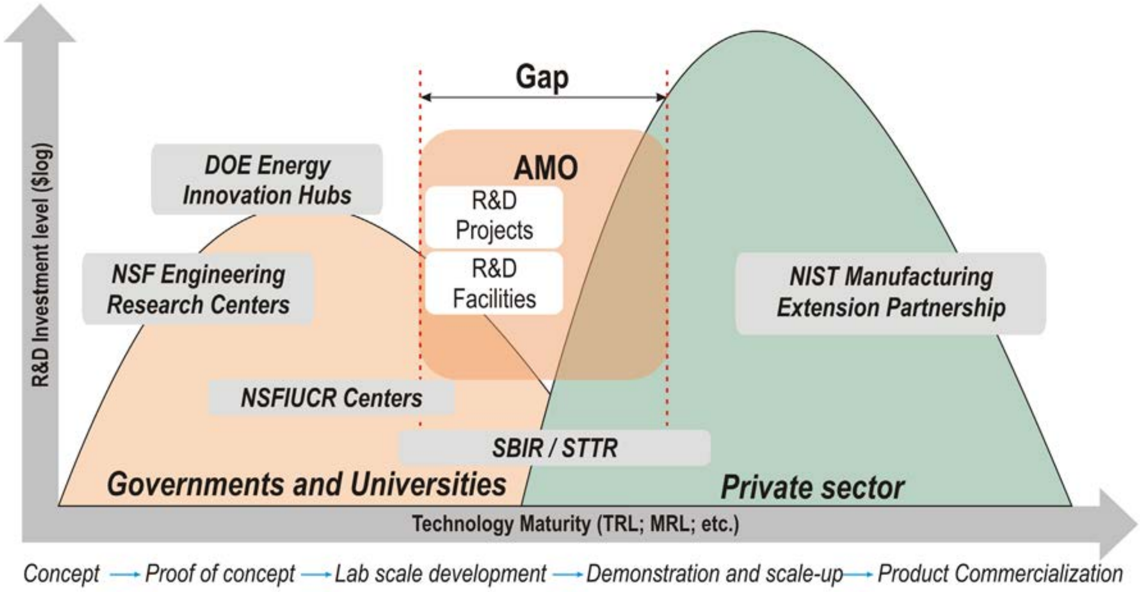


Figure 26: Overview of RDD&D investments in energy technologies (US DOE, 2014)



Increased RDD&D efforts on deployment

This could help push some technologies into the mainstream and the emphasis on deployment will help industry in Singapore gain a competitive advantage through more energy efficient operations. Additionally, working in close partnership with industry to deploy technologies would give researchers a better sense of the practical challenges and opportunities within the industry, which could lead to more useful research in the future. One example of this approach is Sustainable Development Technology Canada (SDTC), which partners with industry to help commercialise clean technology and strengthen Canada's economy. Another example would be government sponsored programs which provide technical and financial support to quantify potential energy savings opportunities; essentially an industrial demand-side management program. A final example would be support for joint academic-industry technology demonstrations. All of these recommendations center around the need for more RD&D funding to be focused on the TRL range of 3 to 8.

International Collaboration

Collaborate internationally on RDD&D in game changing technologies. Certain technologies under consideration show large potential to improve energy efficiency, and are of major interest around the world. For such important global technologies collaborative research efforts should be developed to advance these mutual goals. One example of an area of important international focus would be catalyst research in the refining and chemicals subsector. Given the scale of the global refining industry, Singapore should align its RDD&D programmes with international efforts.

Furthermore, holistic overall plant design, architecture, and process integration schemes for MNCs are handled back in their overseas HQ or corporate RDD&D labs, while the local engineers' responsibility tends to be device-based or unit-operations based. International collaborations with overseas RDD&D labs may enable the design and deployment of technologies that fulfill corporate priorities, while serving Singapore's energy efficiency needs.

One example of this recommendation for governments, from the IEA (International Energy Agency, 2013) to help accelerate technological progress in promising technologies is to create new forms of public-private partnerships (PPP). Such partnerships could enable governments, RDD&D institutions, industry, and technology suppliers to work together to organise, fund, screen, develop and demonstrate selected technologies in shorter time frames. The partnerships could help in numerous ways including: developing and communicating a common target, organising workshops, summarising progress, and supporting top candidate projects. The partnerships would ideally include several levels of interaction that can facilitate collaboration among government laboratories, academic partners, technology developers, and financing entities to help reach the overall objectives. One example of an area of important international focus would be Green Chemistry (Pharmaceuticals).

Subsector-specific recommendations

Petroleum Refining and Chemicals Further research into advanced separations processes. Separations consume a large part of overall energy consumption, and this area is considered to have significant potential for improvement. There are many promising separation processes, each with a specialised application that could be improved. Some specialised applications may not be developed without RDD&D support, and there is some opportunity in this area to help develop processes more beneficial to industry in Singapore than elsewhere. Examples of this research could take similar forms to many of those presented for the previous recommendations (support for joint academic-industry research projects, international collaboration, etc.).

Semiconductor Further collaboration, research and organisational change management support for Advanced Product and Process Control. Achieving Advanced Product and Process Control has far reaching benefits that include a high potential for energy savings. This measure requires different thinking and consideration of specific processes.

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