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Sustainable chemical manufacture and economic prosperity flowing as One

(Background Paper for Plenary Session 7 of the Programme)

Final Draft

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Sustainable chemical manufacture and economic prosperity flowing as One

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Foreword

The theme for the Seventh Regional 3R Forum in Asia and the Pacific is '***Advancing 3R and Resource Efficiency for the 2030 Agenda for Sustainable Development***' with the expected outcome to provide innovative and smart solutions in terms of policy, institution, technology, infrastructure, financing and partnerships for implementation of the Ha Noi 3R Declaration as well as insights into achieving the Sustainable Development Goals under the 2030 Sustainable Development Agenda.

The scope of this background paper is to highlight: (a) the importance of chemistry to the 2030 Sustainable Development Agenda; (b) the state of the chemical industry in Australia and the industry-and academia-wide frameworks that have been developed; (c) the nature of chemical waste and the cross-section of international and regional responses; (d) the emergence of green chemistry and in particular Flow Chemistry as an economically feasible approach.

The background paper on '***Sustainable chemical manufacture and economic prosperity flowing as One***' has been prepared by CSIRO as an input into the Seventh Regional 3R Forum in Asia and the Pacific, in Adelaide, Australia on 2 to 4 November 2016. The paper seeks to highlight the importance of academic, governmental and industry collaboration to implement sustainable chemical manufacturing practices.

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Acknowledgments

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Executive summary

Chemistry plays a critically important role in human development, but also poses many sustainability challenges to mitigate the deleterious effects of this industry on the environment and resource consumption. Green chemistry is a philosophical approach that seeks to look at chemical processes and manufacture holistically, with a view to systematically improving the overall efficiency.

This background report analyses the importance of sustainable chemical manufacturing toward the Sustainable Development Goals (SDGs) and analyses the Australian industry's position relative to these ambitions. Chemical waste continues to be a major policy driver for many countries and Australia and a cross-section of the Asia-Pacific region's responses to these challenges is reviewed.

While sustainable chemical manufacturing is clearly a laudable goal, making the transition involves a difficult and costly investment decision for many firms. Flow chemistry is presented as a potential technological solution that begins to address many of the SDGs by dramatically improving a range of processing parameters, including: better processes and less waste generation; better scalability due to compact, efficient and modular reactor design; smaller physical footprint resulting in reduced capital, operating and maintenance costs; and superior inherent safety. Two cases from the fine chemical manufacturing industry are presented in detail, which demonstrate these benefits.

This report concludes by framing the overall socio-technical challenge faced by the chemical industry, and finds that further education and collaboration between industry, academia and governments is critical for future prosperity.

Part I Chemistry and Human Prosperity

1 Why is chemistry important for sustainable human development?

1.1 Introduction

Chemical manufacturing is a paradox that presents many rewards, but also many challenges, to sustainable human development. On the one hand, there is an undeniable link between chemicals and the increased quality of life they engender through health, agriculture, and the positive effects of industrialisation. This fact is highlighted by the recognition and support of the United Nations Industrial Development Organization (UNIDO) for developing in-country pharmaceutical industries through the Accelerated Industrial Development Agenda for Africa, which aims to improve access to medicines and health care (UNIDO 2015). On the other hand, there is an undeniable link between chemicals and the devastating impact their manufacture and resulting waste can have on health and the environment. This impact has been demonstrated by a number of catastrophic plant failures, with impact over the longer term on environmental contamination and degradation. The importance of chemicals and sustainable chemical manufacturing is therefore consistent with the 17 UN Sustainable Development Goals (SDGs), as outlined in Table 1 (UNDP 2015):

Table 1. Alignment of Sustainable Chemical Manufacturing with the UN Sustainable Development Goals

SDG Goal	Focus	Relevance of Chemistry to SDG
Goal #1	Poverty	Sustainable chemical manufacture of medicines and quality job creation.
Goal #2	Food and Ag	Sustainable chemical manufacture of fertilisers and pesticides to ensure the widespread accessibility of efficient agricultural practices and production of food.
Goal #3	Health	Sustainable chemical manufacture of medicines, insecticides, repellents, larvacides.
Goal #6	Water	Sustainable chemical manufacture to reduce waste pollution and also to develop new chemistries and processes for waste water treatment.
Goal #9	Industrialisation and Innovation	Sustainable chemical manufacture for greening industry through cleaner production approaches.
Goal #11	Cities	Sustainable chemical manufacture to make cities cleaner and safer.
Goal #12	Sustainable Production and Consumption	Sustainable chemical manufacture that delivers the chemicals required to meet human needs, but that reduces the consumption of natural resources.
Goal #13	Climate Change	Sustainable chemical manufacture that reduces emissions through more efficient chemical reaction processes.
Goal #14	Conserve the Ocean	Sustainable chemical manufacture that reduces the production of hazardous wastes that can have a negative impact on ocean ecology.

Goal #15	Conserve the Land	Sustainable chemical manufacture that reduces the production of hazardous wastes that can have a negative impact on terrestrial ecology.

Given the importance of chemistry to sustainable human development, the goals of the Green Chemistry movement are to focus on positive life-enhancing aspects of the chemical industry through the implementation of science and technology programs that reduce inputs and outputs in chemical manufacturing. The aim is to limit the consumption of resources and the production of hazardous substances. More simply, Green chemistry is ‘a philosophical approach that underpins all of chemistry and has technological, environmental, and society goals’ (UNEP 2013).

1.2 The chemicals and plastics industry in Australia

1.2.1 Overview

The Australian Chemicals and Plastics Industry should be seen in two different contexts: 1) as an interdependent part of the international chemical industry, and 2) as an industry that supports the Australian manufacturing sector by direct provision of chemicals and services to Australian firms. In world terms it is a small player, accounting for approximately 1% of world chemical production. Up until the 1980s the industry was heavily protected by the government through tariffs and other mechanisms; these protections were removed over the latter part of the 20th century. Interestingly, even though Australian firms spend less on research than comparable firms overseas, Australia maintains a strong profile in chemical research, with chemical innovation from the universities and publicly-funded research agencies contributing new products and processes to the sector. An important feature of the Australian Chemicals and Plastics sector is how integrated it is with other industries. The Chemicals and Plastics sector provides inputs to 109 of Australia’s 111 industries (Figure 1). As a key input provider, the sector can remain invisible regarding the ubiquity of its products and the value they provide to people’s lives. Only when there is a supply chain disruption does the sector become more visible (Cook *et al.* 2013).

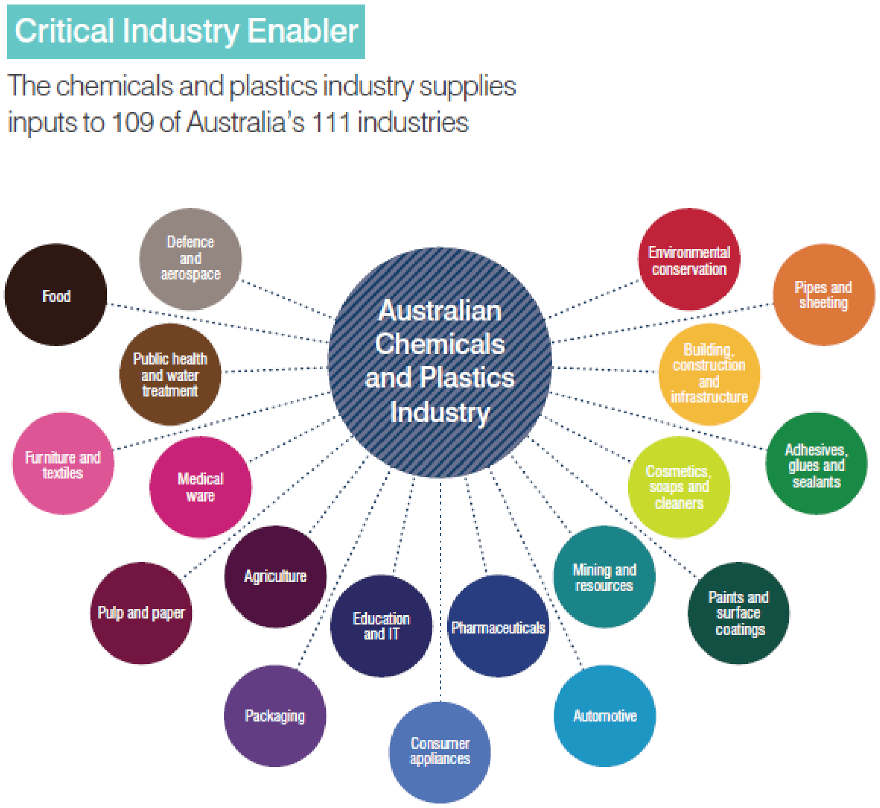

Figure 1. The Chemical Industry in Australia is a Critical Enabler of Manufacturing (PACIA 2014) (reproduced with permission from PACIA)

1.2.2 Strategic Framework Development

The industry recognises that it currently sits at a crossroads, particularly in terms of manufacturing in Australia. The Plastics and Chemicals Industries Association (PACIA), which represents the majority of Australian chemical companies, has recently prepared and released a strategy for sustained growth. In addition to renewing the imperative to drive environmental sustainability, this roadmap for the future highlights the importance of feedstock development (domestic gas as the main source), the importance of harmonised regulation to support a productive industry, and the key role that research and innovation will play in addressing national needs (PACIA 2014). In addition, a social licence to operate is part of their mandate and they have developed a Sustainability Leadership Framework (PACIA 2008).

Complementing this plan, the Australian Academy of Science has also released a Decadal Plan for Chemistry in Australia, with similar findings that strongly highlight the issues of chemical impact and the need for focused innovation (AAS 2016).

The Australian Academy of Science has stated that ‘New opportunities will arise from more sophisticated chemical synthesis that can help with waste minimisation, energy efficiency, zero waste and recyclability’ (AAS 2016, p. 18). Moreover, sustainable chemistry will provide options in the future, including: a new plastic economy; sustainable battery technology; cheaper water purification; high-efficiency fuel cells; environmentally benign pesticides and herbicides (AAS 2016).

Collectively, within Australia the above mentioned plans position and provide a strategic framework for industry, academia, and government to collaborate and drive the necessary reforms for growth and sustainability.

1.2.3 Social Licence to Operate

The pressure on industry, from legislators and non-government organisations generally, to move to a sustainable future has impacted the chemical industry ahead of many other industries. Accordingly, much leadership in sustainable practice has been driven by firms, both individually and through the work of industry associations.

Despite this work, the reputation of the chemical industry is still poor. Information on public opinion in the UK of the chemical sector shows a net unfavourable shift year on year between 1979 to 2002 (Johnston 2012). Historic chemical disasters have contributed to poor public perception of the industry. One of the most significant occurred in 1984 in Bhopal, India. At least 3,000 people died and over 500,000 people were injured as a result of a toxic gas leak from a Union Carbide India Ltd pesticide plant (Allen 2000). In Niagara Falls, New York, the 1978 Love Canal incident forced an entire neighbourhood to be abandoned as a result of toxic chemicals (Hoffman 1995). Continued media coverage of smaller incidents such as facility leaks, as opposed to the positive contributions of the sector, continues to reinforce the negative public perception of the sector.

A negative public perception ensures that the positive contributions made by the industry to society, remain invisible. That the chemical industry has a role to play in securing and boosting food production with pesticides and fertilisers, or helping to reduce carbon emissions, is often lost on the public consciousness (Johnston 2012).

In response to unfortunate global incidents and negative public perception, the chemical sector has made significant progress on implementing voluntary codes of practice or guidelines. The USA developed the American Chemistry Council's Responsible Care Program (ACC 2016) and Australia adopted this program in 1989. It is now a key program under the Australian Plastics and Chemicals Industry Association (PACIA) Sustainability Leadership Framework (Cook *et al*. 2013). Australia also has the Sustainable Packaging Alliance, which is the global distributer for PIQET – an environmental impact assessment to assist environmentally sound design of packaging[1]. These voluntary codes commit members to continuously improving their impact on health, safety and the environment. Voluntary industry standards complement regulation and assist business to adapt to technological and social change (SCSKASC 2012).

1.3 The growing importance of green chemistry in sustainable chemical manufacture

The concept of green chemistry was formulated in 1991. This scientific field aims to demonstrate that next generation products and processes can be profitable while also being good for human health and environmentally benign (Anastas and Eghbali 2010). Since then, many scientific programs, research centres and increased government investment have assisted the growth of the discipline. This includes the $73 m Australian Green Chemical Futures Building, for research, innovation and collaboration with national and international partners at Monash University. The building was completed in 2014[2].

Green chemistry is defined as 'design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances' (Anastas and Eghbali 2010). The most important concept of green chemistry is design, which is reflected in the internationally accepted Twelve Principles of Green Chemistry, which include waste and pollution prevention. These concepts are internationally accepted, but the challenge still remains for taking green chemistry from the research sector to adoption within industry (Figure 2).

1. Waste Prevention	5. Safer Auxiliaries	9. Catalysis
2. Atom Economy	6. Energy Efficiency	10. Degradability
3. Safer Synthesis	7. Renewable Feedstocks	11. Pollution Prevention
4. Safer Products	8. Derivative Reduction	12. Accident Prevention

Figure 2. The Twelve Principles of Green Chemistry (adapted from Sanderson, 2011)

Industrial utilisation of greener technologies still represents only a small fraction of worldwide production (Clark 2006). The manufacture of bulk chemicals is undertaken on a much larger scale than pharmaceuticals, and by comparison produces much less waste. Pharmaceutical plants

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[1] http://www.sustainablepack.org/default.aspx

[2] http://www.eng.monash.edu.au/news/shownews.php?year=2010&nid=30

generate between 25 and 100 kg of waste per 1 kg of product, whereas petrochemicals are closer to 1 kg of product to 0.1 kg of waste. This may explain why the pharmaceutical sector has more readily implemented green chemistry solutions (Sanderson 2011). There are technical challenges to overcome, such as identifying efficient green solvent substitutes for chlorinated solvents, eliminating the need to use toxic metals as catalysts, and finding efficient renewable feedstocks for the development of bulk chemicals (Sanderson 2011). Another barrier to industry adoption is mindset. Chemistry training doesn't include product design or life cycle analysis, thereby excluding education on the consequences of chemical manufacture. Change is needed in education and policy makers need to shift from pollution control to supporting or encouraging the use of green chemistry processes (Sanderson 2011). Regardless, the ever-increasing scientific interest and investment in this field, coupled with the problems that it solves for the chemicals sector, mean that green chemistry will have a significant influence on the future development of new chemicals and processes.

1.4 Summary

Overall, the chemical industry plays a critically important role in society, but is beset on all sides by concerned public and uncertainly about its negative impacts on the environment and societal health. Green chemistry based approaches provide potential answer to these concerns, but the critical question remains: how do we implement green chemical approaches in an economically feasible manner?

2 Chemical waste

2.1 Introduction

The term chemical waste is often used interchangeably with hazardous waste. Hazardous waste has one or more of the following traits: ignitability; reactivity; corrosivity; toxicity. Most chemical waste is in liquid or semi-liquid form, but can also be in gaseous or solid form. Hazardous waste is increasing due to increased demand for goods and services due to population growth, growth in trade of chemical products, increased hazardous components in household waste and improved health care that has led to increased clinical and pharmaceutical waste. Within developed nations, it is common for tracking systems to report the quantity, type and shipment of waste. Treatment is generally undertaken at a treatment centre before residues are disposed of to landfill (Chung and Lo 2003).

Economic benefits drive the illegal dumping of toxic waste. The proper disposal of toxic waste for a European company can be $1000/tonne. However, to illegally dispose of it could cost a paltry $2.50/tonne. This is a serious global issue that requires international collaboration between developed and developing nations. Illegal dumping or shipping of waste to developing nations, which lack proper infrastructure to adequately process waste, results not only in the transfer of waste for treatment, but the export of environmental pollution, which has lasting effects on the nation receiving the waste (Song *et al*. 2015).

This reality has led to three multilateral agreements to control and mitigate the effects of hazardous chemicals and hazardous wastes: the 1989 Basel Convention – Control of Transboundary Movements of Hazardous Wastes and their Disposals; the 1998 Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade; and the 2001 Stockholm Convention on Persistent Organic Pollutants (UNSKDP 2011). The Basel Convention was the first in a string of policy interventions to control the movement of chemical waste. This response was electrified by the spectra of toxic ships transporting their waste around the world (The Basel Convention Secretariat 2011).

There is also a significant problem with plastic waste. In Asia there is a great deal of plastic packaging waste going to landfill. In PR China, non-biodegradable waste is sometimes referred to as ‘White Pollution’ (Song *et al.* 2015). Plastic waste is a major component of marine waste. Marine litter has far-reaching economic consequences such as reducing tourism and fouling of fishing gear, as well as the direct costs of collecting marine debris (Hardesty *et al.* 2014). Marine litter and coastal debris can have measurable economic impacts. In South Korea, one significant rainfall event resulted in significant marine debris being washed onto beaches. The 63% reduction in tourism equated to a revenue loss of between $29 m and $37 m (Jang *et al*. 2014).

2.2 Chemical waste in Australia

2.2.1 Overview

Australia is a signatory to the Basel Convention, the Rotterdam Convention, and the Stockholm Convention. The Hazardous Waste Act 1989 regulates import and export of waste. In 2009–2010 there was a total 3,500,000 tonnes of hazardous waste generated in Australia, of which controlled waste was 188,000 tonnes (ABS 2013). Australia is also impacted by marine debris, much of which is plastic waste from domestic and international sources.

Australia has a similar program to the US TRI, the National Pollutant Inventory (NPI), which tracks 93 substances that may negatively impact human health and the environment. This information is made publicly available through the Department of Sustainability, Environment, Water, Population and Communities (NPI 2016).

2.2.2 Policies for the reduction and/or elimination of hazardous waste generation

Waste management is the responsibility of the eight Australian states and territories and is covered by various levels of legislation (BCF Australia 2011). In 2009, the Australian Government implemented a National Waste Policy, which has six key areas:

1. Taking responsibility – Shared responsibility for reducing the environmental, health and safety footprint of products and materials across the manufacturing supply consumption chain and at end-of-life.

2. Improving the market – Efficient and effective Australian markets operate for waste and recovered resources, with local technology and innovation being sought after internationally.

3. Pursuing sustainability – Less waste and improved use of waste to achieve broader environmental, social and economic benefits.

4. Reducing hazard and risk – Reduction of potentially hazardous content of wastes with consistent, safe and accountable waste recovery, handling and disposal.

5. Tailoring solutions – Increased capacity in regional, remote and Indigenous communities to manage waste and recover and reuse resources.

6. Providing the evidence – Access by decision makers to meaningful, accurate and current national waste and resource recovery data and information to measure progress and educate and inform the behaviour and choices of the community.

2.3 Chemical waste in PR China

2.3.1 Overview

2.3.2 PR China is a signatory to the Basel Convention, the Rotterdam Convention (Hong Kong and Macao Special Administrative Area), and the Stockholm Convention (Hong Kong and Macao Special Administrative Area). In 2005, PR China enacted the law on the Prevention and Control of Environmental Pollution by Solid Waste of the People's Republic of PR China Policies for the reduction and/or elimination of hazardous waste generation

The 2005 Law stipulates: The principle of prevention of environmental pollution caused by solid waste in PR China includes reduction of the generation and harm of solid waste, recycling and disposal of solid waste in an environmentally sound manner (BCF PR China 2011).

In the Hong Kong Special Administrative Region, the policy framework for the Management of Municipal Solid Waste for 2005–2014 advocates waste avoidance and outlines three approaches for a sustainable waste-management strategy:

1. Waste avoidance and minimisation.
2. Reuse, recovery and recycling.
3. Bulk reduction and disposal of unavoidable waste.

Macao Special Administrative Region, PR China Macao Environmental Protection Agency, has launched the 'Macau Environmental Protection Plan (2010–2020)' and organised different forms of public consultation in 2011. Especially in the concerning areas of solid waste disposal and recovery, it proposed many suggestions for strengthening hazardous waste management and optimising disposal systems in the short, medium and long terms.

2.4 Chemical waste in Japan

2.4.1 Overview

Japan is a signatory to the Basel Convention, the Rotterdam Convention, and the Stockholm Convention. The control of chemical waste is covered by four pieces of legislation: the Waste Management and Public Cleansing Law, the Law for Promotion of Effective Utilization of Resources, the Container and Packaging Recycling Law, and the Electric Household Appliance Recycling Law (BCF Japan 2011).

2.4.2 Policies for the reduction and/or elimination of hazardous waste generation

In 1994, the Basic Environment Plan and the Basic Law for Establishing a Sound Material-Cycle Society were enacted. The Basic Law aims to:

1. Restrict generation.
2. Reuse.

3. Recycle.
4. Recover heat.
5. Correctly dispose of waste.

2.5 Chemical waste in Malaysia

2.5.1 Overview

Malaysia is a signatory to the Basel Convention, the Rotterdam Convention, and the Stockholm Convention. The control of chemical waste is covered by the Environmental Quality Act 1974 and the Environmental Quality (Scheduled Wastes) Regulations 2005 (BCF Malaysia 2011).

2.5.2 Policies for the reduction and/or elimination of hazardous waste generation

Frameworks such as the Malaysian Agenda for Waste Reduction focus on key areas such as:

1. Waste minimisation.
2. Recycling, recovery, treatment and safe disposal.
3. New methods of tackling pollution in priority areas.
4. The development of control measures for the prevention and abatement of pollution.

The Malaysia Investment Development Authority also provides incentives for:

1. Storage, treatment and disposal of toxic and hazardous waste.
2. Waste recycling activities.
3. Energy conservation.
4. Energy generation activities using renewable energy resources.
5. Generation of renewable energy for own consumption.
6. Obtaining Green Building Index certificates.
7. Accelerated capital allowances for environmental management.

2.6 Chemical waste in Singapore

2.6.1 Overview

Singapore is a signatory to the Basel Convention, the Rotterdam Convention, and the Stockholm Convention. In November 1997, Singapore enacted the Hazardous Waste (Control of Export, Import and Transit) Act (HWA).

2.6.2 Policies for the reduction and/or elimination of hazardous waste generation

The strategies taken to manage hazardous wastes include (BCF Singapore 2011):

1. Avoid/reduce generation of hazardous wastes.
2. Use less hazardous chemicals.
3. Use clean technology and recycle/reuse toxic industrial wastes where appropriate.

2.7 Chemical waste in Thailand

2.7.1 Overview

Thailand is a signatory to the Basel Convention, the Rotterdam Convention, and the Stockholm Convention. The control of hazardous waste is provided for according to the Notification of the Ministry of Industry B.E. 2548 (2005) issued pursuant to the Factory Act B.E. 2535 (1992) on Disposal of Wastes or Unusable Materials (BCF Thailand 2011).

2.7.2 Policies for the reduction and/or elimination of hazardous waste generation

Thailand has developed an integrated waste management and life cycle approach and developed a strategic plan on special wastes. It has introduced the Polluter Pays Principle by taking into account the responsibility of the producer, importer and consumer.

2.8 Summary

The issue of chemical or hazardous waste and its potential environmental, social and economic impact on nations is ever-present. With increasing population, the projected growth of the Asian middle class, and global demand for goods that rely upon the chemicals and plastics sector, there is an ongoing need to ensure safe treatment and disposal of chemical waste. In particular, there is a strong desire to look at sustainable chemical manufacturing technologies that prevent chemical waste, rather than end of pipe treatment solutions.

Part II Flow chemistry

3 Sustainable chemical manufacture

3.1 Sustainable chemical manufacture

The importance of chemistry and managing chemical waste, and the state of the Australian industry, requires innovation, science, technology and sound regulatory, environmental and social policy to reduce the impact of chemical industry. It must simultaneously harness the benefits chemicals bring to ensure ongoing quality of life and to raise the standard living of billions of people. Moreover, while resource use and human development are inextricably linked, there is ultimately a limited capacity in the environment to absorb the resultant wastes, so there is a practical imperative to reduce waste streams (UNEP 2015).

New approaches to sustainable chemical manufacturing are rapidly gaining momentum, and are driven by the principles of green chemistry, such as addressing the unacceptably high inefficiency and waste production of current processes, safety and energy efficiency. Typical large-scale chemical production is reasonably inefficient. For example, every kilogram of fine chemical produced by the pharmaceutical industry results in the generation of 5 to 100 times that amount of chemical waste. Such low efficiency in organic synthesis presents great challenges in resource conservation and creates new and ongoing environmental and health concerns related to the treatment of chemical wastes.

3.2 Policies, issues and challenges in the implementation of sustainable chemical manufacturing

Matus *et al.* (2015) discussed the difficulties in bringing together the capabilities embedded in industry, academia, and regulators that are needed to develop new green chemistry approaches. In addition to the collaborative effort required, Matus *et al*. highlight the additional paradox that while the benefits of new sustainable green chemical manufacturing may flow to society, they don’t necessarily flow to the company or individual. This disconnect has obvious significant investment implications, particularly for governmental research agencies who typically view industrial research has something that should be funded by companies. Moreover, Matus *et al.* (2015) maintain that green chemistry as a field is ‘competence destroying’, making obsolete the existing processes and incumbents. Therefore, there is an inherent bias against its widespread adoption. As a final challenge, Dunn (2013) contrasts the environmental benefits of developing green second-generation chemical methods, with the economic disincentive wrought by the variability of achieving global regulatory approvals.

Roshchangar *et al*. (2015) discussed the need for a clear set of industry accepted metrics across the chemical industry to enable comparison of chemical approaches. The lack of such metrics is a barrier to the adoption of new processes in the pharmaceutical industry. Sheldon (2016) discusses the thinking around waste minimisation and the development of the Environment) factor (kg waste/kg product) to help drive thinking around the environmental impact of chemical processes.

3.3 Potential business and economic opportunities in reducing chemical waste through process intensification

Despite the challenges outlined above, Satterfield *et al.* (2009) suggest ‘reframing sustainability as an opportunity, investment, and pathway to innovation’. In the green chemistry field there are different approaches to sustainable chemistry, ranging from biocatalysis through to process development (Lorsbach and Sanghvi 2015). An example is flow chemistry, a process which has emerged as a proven technology with a number of advantages for sustainable chemical manufacture (Van Arnum 2013). In Europe, for example, it is now recognised that chemical manufacturers must remain competitive and grow global market share, but at the same time reduce energy and environment costs. The growing trend is to deploy smaller modular flexible plants that are more able to quickly adapt to market changes than traditional large-scale chemical plants (Baker 2015).

Flow reactors for continuous flow processing consist of either tubular pipes or channelled plates in which chemical reactions take place in a continuous stream within a well-defined temporal and spatial environment. Flow reactors offer many advantages over conventional batch reactors, including:

- *Better process control* resulting in higher product yields and purities, shorter reaction times, and less waste generation;
- *Better scalability* due to compact, efficient and modular reactor design;
- *Smaller physical footprint* resulting in reduced capital, operating and maintenance costs; and
- *Superior inherent safety* resulting in lower risk of exposure and catastrophic events.

3.4 Sustainable chemical manufacturing at CSIRO – Flow Chemistry

Over the last few years CSIRO has built up its capability in Flow Chemistry through collaboration, strategic hiring of scientists, and the acquisition of a range of lab and pilot-scale equipment. Through CSIRO’s Flow Chemistry Centre, access to cutting-edge research into industrial flow chemistry is provided to Australian and international chemical manufacturers. The centre houses a state-of-the-art flow chemistry reactor, and downstream processing technologies for the development of sustainable and cost-efficient chemical processes including new chemical routes, process optimisation, and scale-up to pilot and production scale.

Flow chemistry speaks to six of the twelve green chemistry principles: Waste Prevention, Safer Synthesis, Safer Auxiliaries, Energy Efficiency, Catalysis, and Pollution Prevention (see Figure 2).

4 Case Studies

4.1 Fine chemical synthesis – photochromic dyes

In 2011, an Australian company successfully trialled a new flow chemistry synthesis, developed by the CSIRO, to synthesise a high-value photochromic dye. These chemicals play a role in a range of high added-value products that require photo-responsive shading, such as ophthalmic lenses. The pilot flow sequence demonstrated a dramatic improvement in the efficiency of each chemical transformation and significantly reduced the volume of waste generated. Combined, these attributes led to a doubling of final yields and a large reduction in production cost, resulting in a significant overall increase in productivity.

The key learnings from this project about the operation of the flow reactor and the chemistries that perform well can now be applied to the synthesis of many other classes of speciality chemicals. The project demonstrated that all steps of the target photochromic dye synthesis could be performed using the flow reactor, resulting overall in improved yields and significant waste reductions (Table 2).

Using an optimised flow route, a 24% yield for the longest linear sequence (LLS) could be achieved (82% weight yield), compared to 11% LLS (and 40% weight yield) for the batch process. This is effectively more than double the yield from the raw materials used in the batch manufacture of the equivalent chemical. At the same time, a 91% reduction in waste was achieved, with the complete elimination of chlorinated solvent waste from the process.

Table 2. Chemical Yield and Process Mass Intensity (PMI) comparisons for batch and flow processes

	Batch		Flow		Benefits of Flow Chemistry
Step	Yield	PMI	Yield	PMI[a]	
1	85%	119	98%	7	Operationally complex 2-step batch process reduced to simple, solvent-free 1-step flow process
2					
3	70%	173	85%	19	Reduced energy consumption – batch process requires cooling whereas in flow this is performed at room temperature
4	85%	119	98%	5	Solvent-free process used
5	76%	55	81%	31	Hazardous reagent can be replaced with safer and cheaper alternative
6	75%	64	71%	11	No need for chromatographic purification. Hazardous solvent can be replaced with more environmentally friendly alternative

[a] Process Mass Intensity (PMI) is the amount of material required (reagents, solvents, etc. in kg) to produce 1kg of product.

Throughout the course of the synthesis a number of improvements over the batch process were made. Highlights of these included the reduction of a complex 2-step acylation process to a solvent-free flow process. When performed in batch this reaction required the use of a hazardous metal reagent and generated large amounts of chlorinated solvent and aluminium waste.

Table 3. Waste production and energy use comparison for batch and flow processes

	Batch	Flow
Chlorinated waste	218 L	0 L
Non-chlorinated organic waste	612 L	73.5 L
Contaminated aqueous waste	418 L	32.5 L
Liquid waste	1,248 L	106 L (>90% reduction)
Energy	18.5 kWh	1.6 kWh (>90% reduction)

A further highlight was the conversion of an alkylation/hydrolysis reaction series to flow. In the batch process this required cooling to –78 °C to offset the formation of large amounts of heat and resulting degradation in the purity of the final product. Flow systems have inherently more efficient cooling due to their large surface area to volume ratio. This meant that the reaction could be performed at room temperature, generating large savings in both plant costs (the performance of large-scale chemical reactions at very low temperatures requires the use of specialised and costly equipment) and energy usage. A comparative energy analysis of this reaction step found that in order to produce 1 kg of product, energy consumption was reduced by over 90% from 18.55 kWh to 1.62 kWh (a cost saving of around $3.88 per kg of product) (Table 3).

4.2 Fine chemical synthesis

As part of a strategic alliance between a local Australian custom chemical manufacturer, Boron Molecular, and the CSIRO, a new continuous flow manufacturing process for a reactive intermediate was developed. This intermediate is a key reagent for a series of high value added products in the pharmaceutical, agrochemical and functional organic materials area. The synthesis of this intermediate uses a volatile, toxic, flammable, corrosive and highly odorous reagent, which makes it difficult to handle at large scale. Additionally the reaction, which progresses best at elevated temperatures, is exothermic and produces large amounts of hydrogen as a by-product. The characteristic greatly complicates control over the reaction on large scale inside a classical batch stirred tank reactor. Furthermore, another solid by-product of the reaction is produced in higher levels using large-scale batch processing, which complicates the work-up. For the named reasons, manufacture of this product at scale has been extremely challenging and was carried out at lower than optimal temperatures, usually around room temperature. For the batch process this meant that reaction progression was extremely slow, while the vigorous gas evolution inside the stirred tank still required an enhanced level of process monitoring and control. A further complication of the reaction was that it required removal of odorous off-gas via a scrubber. This was more problematic at larger scale, and in the extreme case could lead to the release of considerable amounts of off-gases into the environment. Using the new flow chemistry approach, large evolutions of gas over a short period of time can be avoided, as only a small amount of material is processed inside the reactor at any given time. Hence the release of the gaseous by-product is spread over the entire processing time of the reaction, and can therefore be better controlled. Due to the enhanced control over the heat transfer of the process, the reaction temperature can also be raised significantly, which greatly reduces the reaction time. While the batch process operating at 20 to 25 °C required 7 days to complete, the flow process at 80 °C was reacted with a residence time (the comparable reaction time) of only 10 minutes. These changes led to a significantly safer and more economic process and produced product with higher purity and yield. The space time yield (STY), which is an indicator of the efficiency of the reactor and which is defined as the amount of product yielded per unit time and normalised on the reactor volume, was increased from 0.44 to 1336 g L^{-1} h^{-1}. This in turn means that any continuous plant for the production of this valuable intermediate can be drastically reduced in size, as a much smaller reactor volume is required, and this ultimately results in lower operating costs.

In summary, the benefits of the continuous flow process over batch are:

- reduction of reaction time from 7 days to 10 minutes
- greatly increased control over hydrogen evolution during reaction, and reduction of issues associated with odorous off-gases
- greatly enhanced control over heat transfer and reaction temperature, leading to enhanced process safety
- improved purity of the crude reaction mixture
- lower volume of solvent required, reducing raw material and waste disposal costs
- greatly increased space time yield: batch 0.44 g L^{-1} h^{-1} / flow 1336 g L^{-1} h^{-1}
- reduction of reactor footprint and required plant space

For challenging chemical synthesis operations such as the one described above, especially where control of exothermic reactions and handling of hazardous or gaseous chemicals is a concern, continuous flow processing can provide a much more cost effective, resource and energy efficient and safer alternative to batch.

4.3 Summary

Overall, these case studies demonstrate the holistic benefits of Flow Chemistry from an economic and environmental perspective. This type of approach, coupled with the ease of translating these processes to a larger scale, provides increased confidence in making future investment decisions.

5 The way forward

5.1 Introduction

The above cases demonstrate that green processes can provide a competitive advantage through reduction in waste and production cost, while simultaneously improving efficiency. The most significant obstacle will be assisting decision makers to envision this greener future, particularly when they must maintain their current productivity and revenue. The reality is that researching greener alternatives incurs a cost on business.

Anadon *et al*. (2015) highlight that while technologies have the potential to shape the future, unless we adjust the rules that govern investment in innovation, future sustainability will not be achieved. They suggest three tactics:

1. Understand innovation as a complex adaptive system
2. Understand the socio-technical nature of innovation systems:
    - Technology and society are co-produced
    - Socio-technical characteristics diagnose barriers to innovation
3. Understanding how actors shape and are shaped by innovation systems.

It is also important to reiterate the insight provided by Matus *et al.* (2012) stating that while benefits of new sustainable green chemical manufacturing may flow to society, and can be considered as ‘of high-public good’, they do not necessarily flow to the company or individual. Unless this paradox, which is underpinned by Anadon’s socio-technical factors, can be unpacked and understood, then society will remain in a holding pattern. Practically, tax incentives, access to inexpensive capital, and technical assistance for implementation would all aid in a green transition. Dunn (2013) suggests that if globally harmonised approvals for new chemical processes could be achieved in 12 months, this would make a difference in the ability of companies to forward plan their investment returns in such processes.

At an organisational level, different socio-technical characteristics impede the uptake of green chemistry initiatives. Tucker and Faul (2016) discuss these impediments and suggest the following strategies for effecting organisational uptake of green chemistry initiatives:

1. Empower champions
2. Raise awareness
3. Expand collaborations
4. Define metrics
5. Recognise achievements
6. Invest in technology
7. Promote outreach.

These types of tactics provide decision makers with concrete options to initiate action plans within their organisations and provides a framework to foster green chemistry thinking and creativity to drive holistic process improvements.

5.2 Sustainable chemical manufacture and economic prosperity flowing as One

The challenges for sustainable chemical manufacturing are substantial, multifaceted, and ongoing. However, Australia is well positioned to continue its leadership in the chemistry industry. The industry of the future will be less of a chemical manufacturing and sales business and more of an industry based on chemistry providing solutions to the problems that society faces. The current problems we face are:

- How can we provide improved benefit with less chemical load on the environment?
- How can we reduce the potential for harm from, for example, waste production or the risk of catastrophic plant failure?

Uniquely Australia is an ideal sized economy to do address these challenges. Australia is small enough that true community collaboration across sectors is possible and is large enough as an industry to make a significant contribution to the Asia-Pacific region. Importantly, there are now consistent roadmaps from industry, academia and government to guide the future of the industry. The next step is to make collaboration across sectors easier. In order to do this, Australia must develop a common language across the sector, so that government policy can be used to drive innovation.

A major challenge is still harmonisation of regulation – across state boundaries inside Australia and across nation states in the region. Harmonisation is occurring, but increasing collaborative mechanisms between industry and regulators should speed the consultation and precautionary processes necessary, and hence allow increased investment.

Education and training is a key driver of increased collaboration. Currently in Australia, chemistry business pathways are siloed into academic, industry or government agency frameworks. While technical and business education is clearly world-class, there could be more focus on those scientists who will become the collaborators and policy makers of the future. With the industry and science roadmaps in hand to guide the skills necessary, Australia is now in a position to craft new courses and qualifications.

There are multiple approaches to waste handling and sustainable business practice and there is much debate on the role of renewable energy and on the best way to exploit and manage Australia's gas reserves.

- Should gas production be reserved for the purpose of chemical feedstock?
- How does chemistry support the next generation of solar and other renewable energy sources and how do we develop coherence across the nation?

Clearly, these questions highlight the fact that the chemical industry in Australia is not a standalone industry and is intimately linked downstream with the oil and gas industry and upstream with inputs to almost all sectors of the economy. We now stand able to address these questions as a community with a clear sustainability framework.

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