GREEN CHEMISTRY &
COMMERCE COUNCIL
Business Mainstreaming Green Chemistry

Measuring Progress towards Green Chemistry

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www.greenchemistryandcommerce.org

About the Organizations

GREEN CHEMISTRY & COMMERCE COUNCIL (GC3)

The GC3 is a cross sectoral, business-to-business network of companies and other organizations working collaboratively to advance green chemistry across sectors and supply chains. The GC3 is based in the Lowell Center for Sustainable Production at the University of Massachusetts Lowell. The GC3 commissioned this research to support its efforts to mainstream green chemistry by understanding barriers and opportunities to accelerating green chemistry adoption across supply chains.

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Table of Contents

EXECUTIVE SUMMARY

Metrics play a critical role in understanding if green chemistry design, policy, business, or educational efforts are leading us towards desired outcomes. The purpose of this Green Chemistry & Commerce Council (GC3) report is to identify and characterize metrics that can be used to measure progress in green chemistry. This review is designed to be a comprehensive, though not exhaustive, overview of useful metrics including metrics to measure the advancement of green chemistry at four levels:

1. Molecular/Process-Level;
2. Product and Material Level;
3. Firm and Sector-Level; and
4. Societal-Level.

Societal-level metrics include broad human health and environmental measures. The report also catalogues metrics that measure chemical use and releases; economic and health outcomes; and conformance to the 12 Principles of Green Chemistry (See Table 1).

Table 1: The 12 Principles of Green Chemistry
1. Prevent waste
2. Atom economy
3. Less hazardous synthesis
4. Design benign chemicals
5. Benign solvents and auxiliaries
6. Design for energy efficiency
7. Use of renewable feedstocks
8. Reduce derivatives
9. Catalysis (vs. stoichiometric)
10. Design for degradation
11. Real-time analysis for pollution prevention
12. Inherently benign chemistry for accident prevention

Most metrics identified track reductions in impacts of chemistries of concern to human health and the environment through proxies such as health outcomes, economic outcomes, or chemical use or release, rather application of green chemistry practices per se. A minority of metrics identified directly measure growth and application of green chemistry practices (e.g., tracking use of the 12 Principles of

Green Chemistry or reductions in energy or material use in molecular design), and most of those are at the molecular/process level.

Overall, tools exist at each level that are designed to benchmark and measure movement away from chemicals of potential concern. Few tools currently track progress *towards* greener, more benign chemistries, materials, products and processes. However, there are methods emerging at different points in the supply chain that could provide the basis of more effective measures of progress in green chemistry in the future.

This report concludes with recommendations for creating new metrics that could evaluate green chemistry progress and the development of safer chemicals, materials, products, and manufacturing processes.

INTRODUCTION: WHY METRICS MATTER

The late, legendary economist Milton Friedman used to ask his students two questions: “How do you know?” and “So what?”[1] Without metrics, we do not know if we are heading in the right direction, nor do we know how slowly or quickly we are getting there. Having the right metrics allows us to direct our activities and our resources more intentionally and effectively toward a desired outcome. Furthermore, a search for good metrics can also inform our thinking and sharpen our focus on specific desired outcomes.

WHAT DO WE MEAN BY GREEN CHEMISTRY?

The very task of examining the landscape of metrics available for measuring progress towards green chemistry raises questions about the definition of green chemistry and progress in green chemistry. The first is relatively straightforward, as there is agreement among green chemistry practitioners to use the definition articulated by Warner and Anastas in their seminal book.[2]

> Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances throughout their lifecycles, including design, manufacture, use, and end of life.
>
> Green chemistry is a growing field of practice that builds on conventional chemistry and engineering by applying 12 fundamental principles that guide the molecular design of sustainable chemical products and processes. Following these principles prevents pollution and waste, leads to synthesis of chemicals in less hazardous and more efficient ways, promotes the use of renewable feedstocks, and leads to the design of safer chemicals. [3]

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[1] *Baker, Ronald J. Measure What Matters to Customers: Using Key Predictive Indicators (KPIs) Ronald J. Baker, Wiley, (2006)*

[2] *Paul T. Anastas and John C. Warner (1998)* Green Chemistry: Theory and Practice*; Oxford University Press*

[3] http://www.warnerbabcock.com/green-chemistry/green-chemistry-overview

The Green Chemistry & Commerce Council expands this definition to provide more context about the application of green chemistry:

> Green chemistry incorporates every element of business, from product design to feedstock selection through manufacturing to finished products, including the ways that companies manage their businesses and engage their customers throughout the supply chain.
>
> While green chemistry has been practiced primarily at the chemical discovery, development and formulation levels, product developers, manufacturers, brands and retailers all play an important role in its implementation. Several ways they do this are by changing design specifications, sourcing materials and products that incorporate green chemistry practices, changing manufacturing practices to substitute or reduce the use of hazardous chemicals, and developing and implementing policies that restrict chemicals of concern in the products they source, make, and/or sell.

The Warner-Babcock Institute for Green Chemistry takes this definition a little further:

> Green chemistry offers a different approach to conventional chemistry and engineering through the thoughtful application of principles that aid the design of sustainable chemical products and processes by focusing individuals on the development of innovative solutions, opportunities, and challenges. Applying these principles collectively will result in ***products and processes that protect and benefit the economy, people, and the planet*** and help us make significant strides toward a more sustainable future.[4] *[Emphasis added]*

Green chemistry is frequently embedded in the broader frame of sustainability, particularly at the chemical manufacturing end of the supply chain, and this is reflected in some of the metrics utilized by this sector, as detailed below. At the material and product level, some manufacturers consider human and ecosystem toxicity criteria along with other impact measures such as energy consumption, carbon and water use, and biodegradability or recycling and reuse at end of life.

It’s worth noting that the expanded definitions of green chemistry from the GC3 and the Warner-Babcock Institute suggest potential indicators of what should be measured, namely:

- The reduction or elimination of the use of hazardous substances in the design, manufacture, and application of chemical products;
- Sourcing materials and products that incorporate green chemistry;

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[4] http://www.warnerbabcock.com/green-chemistry/green-chemistry-overview

- Changing manufacturing practices to substitute or reduce the use of hazardous chemicals;
- Developing and implementing policies restricting chemicals of concern in the products companies source, make, or sell.

THE LANDSCAPE OF CURRENT GREEN CHEMISTRY METRICS

Effective metrics should help to lead us toward achieving the goal of safer chemicals, materials, processes and products, resulting in an overall improvement in human health and the environment, and a viable green economy. This report explores the landscape of existing metrics to evaluate whether and how they measure progress toward these goals, based on a broad literature review and interviews with green chemistry experts from industry, academia, and non-profit advocacy groups in environmental health.

This mapping identified a range of metrics to measure progress towards green chemistry at five potential levels of evaluation: (1) molecular/process, (2) product/material, (3) firm, (4) sector, and (5) societal. It should be noted that these level descriptors were developed for the purpose of this analysis. Some overlap exists between levels and some metrics could fall into multiple categories. Largely, existing metrics measure health outcomes, economic outcomes, use and release of chemicals of concern rather than actual green chemistry activity. The most well-developed metrics, which measure progress toward green chemistry, are focused at the molecular level, e.g., tracking progress towards safer molecular design. There are varying opinions on the exactness of molecular level metrics; Constable et al. provide an overview of these discussions in a 2002 review.[5]

Overall, tools designed to benchmark and measure movement away from chemicals of potential concern exist at each level of evaluation. There are few tools currently tracking progress towards greener, more benign chemistries, materials, products and processes. However, tools are emerging at different parts of the supply chain that could provide the basis for more effective measures of progress in green chemistry moving forward. Examples of metrics at each level are provided below.

MOLECULAR/PROCESS-LEVEL METRICS

Molecular level tools have the most direct link to the 12 Principles of Green Chemistry and are fairly well-developed. Metrics include measures of atom economy or efficiency, effective mass yield, and carbon efficiency. There is still some debate about

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[5] *Constable, D. et al., Metrics to 'green' chemistry---which are the best?, Green Chemistry, 2002 , (4), 521-527*

the effectiveness of these metrics, as they do not address all energy and feedstock considerations, reaction types, or life cycle impacts addressed in the Principles.[6]

A 2012 survey conducted by the American Chemical Society (ACS) found that "several green chemistry principles and related metrics are routinely implemented in the chemical manufacturing sector".[7] Ninety six respondents provided information on their companies' use of metrics. Metrics that were most commonly employed were carbon footprint, CO_2 production, water usage and life cycle impacts, with process manufacturing efficiency, E-factor (the ratio of the mass of waste per unit product), and atom economy lagging. Individual companies, in particular within the pharmaceutical industry, have taken great strides in increasing process efficiency. However companies in the pharmaceutical sector or other sectors did not report use of metrics to track the number of chemicals of concern eliminated or the number of new "safer" chemicals introduced.

PRODUCT AND MATERIAL LEVEL METRICS

Product and material-level metrics are used primarily by individual companies. Approaches include the use of selected green chemistry principles as measures for specific products and processes as well as internal benchmarking tools that evaluate movement away from chemicals of concern for a company's entire ingredient palette.

For example, Sigma Aldrich[8] has created a goal for increasing the sales of the company's "greener alternative products" and provides a specific example of green chemistry for one of its products—beta-amylase produced from sweet potatoes. For the example, Sigma reports a reduction in the volume of raw material used, the elimination of 1,700 gallons of acetone, reduction of energy usage by changing the production process, and increased product yield. Each of these improvements is specifically tied to one of the 12 Principles of Green Chemistry.

Biotech company Singlogen similarly ties the environmental benefits of its Singlotex[9] anti-odor technology to the green chemistry principles of minimizing toxicity, using renewable materials, eliminating the use of solvents, increasing energy efficiency, avoiding waste, and including only EPA-approved ingredients as a measure of ingredient safety.

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[6] *L. Hamel & I. Levy, Gordon College, ACS conference, San Diego, 2005;* *http://greenchem.uoregon.edu/ACSGoingGreenSite/PDFs/20050316WedAM/1364Hamel.pdf*

[7] *Giraud, R.J. et al., Implementing Green Chemistry in Chemical Manufacturing: A Survey Report, ACS Sustainable Chem. Eng. , 2014, 2, 2237-2242*

[8] *http://www.sigmaaldrich.com/globalcitizenship/environmental.html*

[9] *http://singlosport.com/technology*

S.C. Johnson describes its GreenList™ approach as "a patented process that establishes comparative criteria that measure the environmental and biological impact of our raw material choices".[10] The company further states that the goal was to "go beyond taking out "bad" ingredients and instead focus on choosing "better" options and continuously improving formulas based on information about ingredients' impact on the environment and human health.[11]"

Service providers have created tools that are designed for benchmarking and comparison of chemical and material hazards. At the chemical level, these include Clean Production Action's Green Screen for Safer Chemicals as well as proprietary tools developed by SciVera and the WERCS (now UL Environment).[12] Material assessment approaches include, for example, the Material Health Assessment of the product-based Cradle-to-Cradle certification process; Material IQ; and, Clean Production Action's Plastics Scorecard.[13] Each of these tools is designed to evaluate the inherent hazard of a chemical or material. Cradle-to-Cradle's Material Health methodology is described as an approach to "knowing the chemical ingredients of every material in a product, and optimizing towards safer materials." Material IQ is designed to facilitate comparisons of material products on the basis of ingredient hazards and is "intended to be a design tool for all manufacturers, providing insight into how to improve their products." The Plastics Scorecard allows for comparison within a major material class based on the hazard of plastics process chemistry. All of these tools are designed to help organizations better understand the hazards of chemicals and materials in their products and processes with the goal of moving to safer chemistries. If used to benchmark existing products and processes, with additional evaluations occurring over time, these tools could potentially be used to measure progress in green chemistry.

FIRM AND SECTOR-LEVEL METRICS

We found the largest number and greatest diversity of metrics at the firm and sector level, but few if any are direct green chemistry measures. Some measures could serve as proxies for green chemistry, for example the US EPA's Toxics Release Inventory (TRI), which tracks the volume of TRI chemicals used, over time. The US EPA is beginning to use TRI data for this purpose[14]. The data can be used to analyze changes

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[10] *Guiney, P., Director of Global Environmental Safety, S.C. Johnson & Son, Inc., S.C. Johnson's Greenlist Program for Raw Material Selection: Pushing the Sustainability Frontier, Minnesota Green Chemistry Conference, January 2012;* *http://www.greenchemistrymn.org/sites/greenchemistrymn.org/files/presentations/Pat%20Guiney.pdf*

[11] *http://www.scjohnson.com/en/commitment/focus-on/greener-products/greenlist.aspx*

[12] *http://www.greenscreenchemicals.org/method; http://www.scivera.com; http://www.thewercs.com*

[13] *http://www.c2ccertified.org/images/uploads/C2CCertified_Material_Health_Methodology_121112.pdf; http://www.materialiq.com; http://www.bizngo.org/sustainable-materials/plastics-scorecard*

[14] *DeVito, S, et al. Can pollutant release and transfer registers (PRTRs) be used to assess implementation and effectiveness of green chemistry practices? A case study involving the Toxics Release Inventory (TRI) and pharmaceutical manufacturers. Royal Society of Chemistry, April 2015. DOI: 10.1039/c5gc00056d*

at firms that report this data to the EPA or for sectors (reported under NAICS codes). The Massachusetts Toxics Use Reduction Act has a similar reporting structure and database for tracking the reduction in use of hazardous industrial chemicals over time through its materials accounting requirements. Metrics found in this category were either designed by a manufacturing company/brand or consulting firm/third-party and were either internal-facing, i.e., designed to communicate progress within the company, or external-facing, i.e., designed to communicate progress outside the company to the public.

Firm-Level Metrics Designed by Companies/Brands

Firm-level metrics that were identified are either designed to be used at the product/material, firm-level or both. These metrics tend to place green chemistry within the broader sustainability context of a firm. Examples include the Dow Sustainable Chemistry Index and AkzoNobel's Eco-Premium Solutions.[15] Both of these company-level approaches have some externally visible measures, but are primarily internal benchmarks.

Dow measures its improvements as "percent of revenue achieved by chemistries advantaged by sustainability" including factors such as renewable/recycled content, life cycle benefit, and manufacturing efficiency. Sigma Aldrich has a goal of increasing the sales of their 2,563 Greener Alternatives Products by 25%. AkzoNobel describes its Eco-premium solutions concept as a "quick scan method to benchmark the performance of AkzoNobel products in six HSE aspects (Health, Safety and Environment) against the most common competing alternative products on the market (mainstream solutions) from a life cycle (value chain) perspective." AkzoNobel's objectives are to: "encourage and stimulate the development and innovation of more sustainable products; measure progress by assessing the share of revenue from eco-premium solutions: and, monitor development toward specific goals."

Firm-Level Metrics Designed by Independent Third Parties

Independent third parties have created the new Chemical Footprint Project and the Michigan Checklist for Green Chemistry. The Chemical Footprint Project (CFP), launched in June 2015, has created an Assessment Tool for businesses to benchmark progress in four areas: management strategy, chemical inventory, progress measurement, and public disclosure and verification.[16] CFP will publicly recognize companies that have created effective chemicals management systems and have succeeded in reducing the use of chemicals of high concern and substituting safer chemistries. CFP was founded jointly by the NGO Clean Production Action, the Lowell

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[15] http://www.dow.com/en-us/science-and-sustainability/sustainability-reporting/sustainable-chemistry; https://www.akzonobel.com/sustainability/managing_sustainability/key_focus_areas/creating_value_eco_premium_solutions

[16] http://www.chemicalfootprint.org

Center for Sustainable Production at the University of Massachusetts Lowell, and the sustainability consultancy Pure Strategies.

The Green Chemistry Checklist, developed by the Michigan Green Chemistry Roundtable, provides a framework for businesses to track green chemistry performance in four areas: education, hiring, design and innovation, and support and communication. While the checklist is intended to build a green chemistry culture in individual firms and provide a framework for benchmarking, the checklist could be used as an external measure of green chemistry progress at the firm level, including in green chemistry training, research and development, commercialization of green chemistry products and green chemistry hiring.

Sector-Level Metrics

Metrics that are designed to be used by firms in a specific sector are still in the very early stages and focus on chemical disclosure; some examples are described below. The Health Product Declaration (HPD)[17] is a template for providing information on chemical ingredients in building materials and their associated health hazards. In the apparel and footwear sector, the Zero Discharge of Hazardous Waste (ZDHC)[18] effort is working toward zero discharge of hazardous chemicals by 2020. The ZDHC is creating templates and gathering data on chemical treatments from over 800 mills that will be checked against manufacturers' restricted substances list (MRSL). Both the HPD and the ZDHC Data Schema, while currently focused on tracking the use of potentially hazardous chemistries in global supply chains, could readily be used to track progress by these sectors toward more benign chemistries. The Natural Products Association (NPA) is an industry group that has generated lists of both banned and preferred chemical ingredients as well as manufacturing processes that meet the criteria for its Natural Seal[19] for home cleaning and personal care products. NPA states that over 1,100 products are now certified to the Natural Seal standards, providing a sector-level metric
for movement towards more benign chemistries.

SOCIETAL-LEVEL METRICS

Metrics at this level include exposure and health-based metrics as well as chemical use-based metrics. Health and exposure based metrics are currently primarily represented by biomonitoring results from testing for the presence of chemicals of concern in human tissue (e.g., the CDC's NHANES: National Health and Nutrition Examination Survey) or in biota (e.g., the San Francisco Estuary Institute's Regional

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[17] http://hpdcollaborative.org
[18] http://www.roadmaptozero.com
[19] http://www.npainfo.org/npa/NaturalSealCertification/TheNaturalSeal.aspx

Monitoring Program that tracks chemical contaminant concentrations in biota in the San Francisco Bay). As with sector metrics, while these outcome-based measures can serve as proxies for a move away from particular chemicals or classes of chemicals, they do not necessarily provide information on substitutes and whether or not those substitutes are preferable.

Health-based metrics are exceptionally challenging to track (for example reductions in disease due to a chemical substitution) given the lag times between exposure and disease, and the multiple genetic, social, and environment factors involved in disease causation. Hence, these have not been used to date in measuring green chemistry progress, though green chemistry solutions have been advocated as a response to some disease trends that have environmental risk-factors, such as cancer.[20]

Governments at the federal, state, and international levels have established societal-level metrics that utilize chemical use and chemical use reduction data. Prominent examples include the Massachusetts Toxics Use Reduction Program, the US EPA's Chemical Data Reporting program, the Nordic Product Registries, and the EU's REACH as well as several product-level chemical reporting regulations at the state level in the US.[21]

The Massachusetts Toxics Use Reduction Act, enacted in 1989 and amended most recently in 2006, "requires Massachusetts companies that use large quantities of specific toxic chemicals to evaluate and plan for pollution prevention opportunities, implement them if practical, and annually measure and report the results."[22] Over the nine-year period from 2000 to 2009, companies reported a 21% reduction in toxic chemical use, a 38% reduction in toxic byproducts, and a 56% reduction in on-site releases of toxics to the environment. These and other TURA measures could serve as models for company and sector-level reductions in the use of hazardous chemicals, and, if used in combination with measures tracking the use of green chemistry alternatives, could provide a clear picture of broad progress towards more benign chemistries.

Similarly, the US EPA's Chemical Data Reporting Requirement of the Toxics Substances Control Act (CDR), "requires manufacturers (including importers) to report on the chemical substances they produce domestically or import into the United States during the principal reporting year. For the 2012 submission period, reporters provided 2011 manufacturing, processing and use data and 2010 production volume

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[20] *President's Cancer Panel, Reducing Environmental Cancer Risk: What We Can Do Now, 2008-2009 Annual Report, April 2010;* *http://deainfo.nci.nih.gov/advisory/pcp/annualReports/pcp08-09rpt/PCP_Report_08-09_508.pdf*

[21] *http://www.epa.gov/cdr*

[22] *http://www.mass.gov/eea/agencies/massdep/toxics/tur/*

data for their reportable substances".[23] Reported data are available in a searchable database; differences in the data reported in 2006 and 2012 could be used to assess reductions and changes in chemical use. While the CDR currently does not specifically track substances produced applying the green chemistry principles, it is theoretically possible to add such a tag to the reporting requirement, perhaps on a voluntary basis.

The Nordic product registries, or SPIN, (for Substances in Preparations in Nordic countries), along with other similar reporting requirements in several US states, are examples of systems that can provide broad tracking of use of chemicals of concern in consumer products. Maine[24] and Washington[25] each have regulations requiring reporting of specific subsets of chemicals of concern in children's products, with the goal of phase-out of the chemicals of highest concern. Notification requirements under the European Union's REACH regulation, specifically the notification of the presence of a chemical meeting the Substances of Very High Concern (SVHC) criteria can also provide metrics for broad tracking of changes of chemical use in manufacturing over time.[26]

Overall, these metrics, with the exception of those at the molecular level, focus on benchmarking and measuring progress away from chemicals of concern rather than a move towards better chemistries. This may be a reflection of the current marketplace, but it does pose the question of what kinds of metrics are needed to help catalyze greater innovation in green chemistry across multiple sectors. Several sets of metrics, particularly the US EPA Presidential Green Chemistry Award criteria[27], may provide a starting point for evaluating progress in green chemistry at the material or product level. Additionally, chemical disclosure tools, both sector-specific and general, have the potential to track movement toward improved chemistries in addition to tracking the continued use of chemicals of concern.

GOING FORWARD: OPPORTUNITIES AND RECOMMENDATIONS

This examination of the current landscape of green chemistry metrics identifies a need and an opportunity to design metrics that can track movement towards a future of greener, more sustainable chemistries, and sustainable product and process design. The review highlights tools at different points along a chemical or product life cycle and supply chain that could provide the basis for more refined and targeted measures of progress towards green chemistry.

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[23] http://www.epa.gov/cdr/pubs/guidance/cdr_factsheets.html#basics
[24] http://www.maine.gov/dep/safechem/
[25] http://www.ecy.wa.gov/programs/hwtr/RTT/cspa/index.html
[26] *Massey, R. et al., Toxic Substances in Articles: The Need for Information, 2008, prepared for the Swedish Chemicals Agency (Keml) and the Nordic Council of Ministers*
[27] http://www2.epa.gov/greenchemistry/information-about-presidential-green-chemistry-challenge

WHAT EXISTING ELEMENTS OF METRICS COULD WE BUILD ON?

The US EPA's criteria for the Presidential Award for Green Chemistry provide a valuable translation of the 12 Principles of Green Chemistry to a product, process, or material. In order to meet these criteria, a product, process or material needs to:

- Reduce toxicity (acute or chronic) or the potential for illness or injury to humans, animals, or plants;
- Reduce flammability or explosion potential;
- Reduce the use or generation of hazardous substances, or their releases to air, water, or land;
- Improve the use of natural resources, for example, by substituting a renewable feedstock for a petroleum feedstock;
- Save water or energy; or
- Reduce the generation of waste, even if the waste is not hazardous.

At the firm level, these criteria could be scaled to track performance across multiple products, e.g., a firm could measure the reduction in toxic chemicals or byproducts per unit of product or product mass and an increase in the use of chemicals deemed as safer per unit product. Measures could also include percent of products "designed with green chemistry principles" or the production volume of "greener" chemicals. Measures could also track building of a "green chemistry culture" within firms, as the Michigan Green Chemistry Checklist does or other tools such as a "maturity ladder", which measures progress towards building a concept within an organization.

A chemical "footprint" of the firm could be measured, utilizing an approach such as that utilized in the Chemical Footprint Project. Firm-level chemical footprints could in turn be rolled up to a sector level to measure, for example, the number of products meeting sector-wide criteria for safer chemistries. Currently 1,100 products meet the Natural Products Association's "Natural Seal" standard, a potential sector-wide metric of movement towards more benign chemistries. The US EPA Design for Environment's Safer Chemicals Ingredients list provides a similar function in identifying safer cleaning chemicals and other formulated consumer and institutional product ingredients. In addition, products containing safer ingredients can be reviewed and labeled under the US EPA's Safer Choice program. US EPA has developed metrics for tracking estimated volumes of products on the market with safer chemistries based on products certified under Safer Choice. The metric could be improved if companies with certified products were required to report sales volumes to US EPA.

Metrics at a broader societal level could be developed to track measures scaled from other levels, or expand to other proxy measures entirely, including economic metrics and human health or environmental improvements. Economic metrics could include:

- Production volume of greener chemicals (potentially reportable under US EPA's Chemical Data Reporting system)[28];
- Number of new chemicals coming to market that follow specific green chemistry principles;
- Number (or production volume) of molecules removed from commerce and replaced with more benign molecules;
- R&D funding or government investment and technical support for green chemistry both in academia and in industry; or
- Green chemistry-related employment and academic institutions with training programs that graduate individuals to fill these jobs.

Metrics that bridge economics and rolled-up metrics from firms and sectors could include:

- Reduction in emissions of problem chemicals (as the Toxics Release Inventory currently does, with a limited set of chemicals; the caveat here is that TRI does not capture chemicals of concern in *products)*; or
- Reduction of chemicals of concern in products; (this could be accomplished by establishing product registries such as SPIN, the registry of Substances in Preparations in Nordic Countries[29], or by regulations such as the Washington State Children's Safe Product Act, which requires both reporting of and testing for certain chemicals of concern in children's products).

Metrics that bridge economics and health outcomes could include measures of reduction in body burden levels of chemicals of concern, biota levels of chemicals of concern, or levels of specific chemicals in sensitive subpopulations such as children, workers, or the immune-compromised. Individual examples of metrics for human body burden or environmental reduction of specific chemicals of concern exist, but remain limited. The CDC's NHANES biomonitoring program[30], for example, tracks a subset of chemicals of concern in the US population, but may not be able to track emerging chemicals of concern or regrettable substitutions; tracking of chemicals in biota can

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[28] http://www2.epa.gov/chemical-data-reporting

[29] *Massey, R. et al., Toxic Substances in Articles: The Need for Information, 2008, prepared for the Swedish Chemicals Agency (KemI) and the Nordic Council of Ministers*

[30] http://www.cdc.gov/nchs/nhanes.htm

show a decrease in chemicals of concern, but to date has been limited in number of chemicals covered, number of species covered, and geography.

POTENTIAL CHALLENGES IN DEVELOPING METRICS

The limited array of current measures of human health and environmental impacts points to one of the key challenges of creating health-based green chemistry metrics at the societal level: identifying causal links between, first, chemical exposure and disease, and second, the removal or replacement of a chemical of concern and subsequent health benefit. While metrics at the societal level can be helpful for tracking body burdens or disease across populations, as noted, there are significant scientific barriers to using these for tracking health and body burden benefits of green chemistry. As such, molecular level metrics are likely to be more actionable. One targeted effort focused on the design of chemicals and materials to reduce toxicity is the Molecular Design Research Network (MoDRN), a four university multidisciplinary research effort. MoDRN's research is focused on the creation of predictive tools to support safer chemical selection.[31]

In addition, while one might be able to track the removal of a chemical of concern, it is critical to evaluate substitutions for that chemical that may or may not contribute to other health and environmental impacts. There are many examples of regrettable substitutions that shift impacts from one environmental medium to another, from an environmental impact to a worker impact, from one human health endpoint to another, or from a human health impact to an environmental impact.

Other challenges of developing metrics include trade-offs and weighting. In addition to the types of regrettable substitution trade-offs described above, trade-offs can include, for example the creation of a product that may eliminate a harmful waste stream or raw material, but may not provide any additional benefit or meet any significant need of an industry or consumer. Does the design and production of such a product qualify as "green chemistry", and who gets to decide?

Issues of weighting can come to the fore, for example, if the reduction of greenhouse gas emissions is prioritized over human health or other environmental impacts. This could result in eutrophication impacts from growing bio-based feedstocks, or the underweighting of human health impacts or ecotoxicity in standard life cycle assessment (LCA) protocols. Similarly, a singular focus on strategies in lieu of outcomes as ends in themselves (e.g., recycled content, plant-based, or "free" of a specific chemical of concern) may lead to unintended consequences by creating an ad

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[31] *http://modrn.yale.edu*

hoc weighting that obscures hidden trade-offs with impacts elsewhere in the product or chemical's life cycle.

While the challenges are not insignificant, this examination of the current landscape of metrics indicates that there is a good foundation being created to track progress toward green chemistry. This is an opportune time to build on successful existing measures to create a clearer path towards the vision of, in the words of the Warner-Babcock Institute "products and processes that protect and benefit the economy, people, and the planet and help us make significant strides toward a more sustainable future."

Appendix A: The Current Landscape of Green Chemistry Metrics or Surrogate Metrics and Related Tools

Levels of metrics, and examples:

- Chemical/Molecular Level
    - iSustain
    - EcoScale
    - Various metrics per ACS review (2002)[32]
    - Presidential Green Chemistry Award Criteria (US EPA)
- Product/Material/Chemical level
    - US EPA Toxics Reduction Inventory
    - US EPA Design for Environment's Safer Chemicals List
    - US EPA Design for Environment's Alternatives Assessment projects (Chemical/Material)
    - Clean Production Action's Green Screen (Chemical)
    - Cradle-to-Cradle Material Assessment (Material/Product)
    - Health Building Network's Pharos (Chemical/Product)
    - Health Product Declaration (Chemical/Material)
    - Blue Green Alliance's ChemHAT (Chemical)
    - Clean Production Action's Plastics Scorecard (Material)
    - Green Blue's Material IQ (Material)
- Firm/Sector Level

    Company-Designed Firm Metrics
    - Sigma Aldrich Environmental Sustainability (Firm)
    - AkzoNobel EcoSolutions for EcoInnovation (Firm)
    - S. C. Johnson GreenList (Firm)
    - Dow Sustainable Chemistry Index (Firm)

    Third-Party Designed Firm Metrics
    - BizNGO Guide to Safer Chemicals (Firm)
    - Chemical Footprint Project (Firm)
    - Michigan Green Chemistry Checklist for Businesses (Firm)
    - B Impact Assessment V4.0, questions on supply chain chemical disclosure for firms with >250 employees

    Sector Metrics
    - Textile/Apparel: Zero Discharge of Hazardous Chemicals (Firm/sector)
    - BlueSign Blue Finder: List of safer textile treatment formulations (Sector/Process)
    - Outdoor Industry Association's Chemicals Management Module/Sustainable Apparel Coalition's Higg Index) (Firm/sector)
- Societal/Environmental Level
    - UNEP Sustainable Development Goals
    - Biomonitoring (Humans and non-human biota)
        - CDC NHANES
        - California Biomonitoring Program
        - San Francisco Estuary Institute Regional Monitoring Program
        - US Geological Survey Environmental Health monitoring

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[32] *Constable, D. et al., Metrics to 'green' chemistry---which are the best?, Green Chemistry, 2002 , (4), 521-527*