

# “Green Chemistry in the Fight Against Climate Change” Kpis, Reporting and Carbon Accountability in Chemical Innovation.

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## ABSTRACT

The chemical industry, which is among the most vital industries to the global economy, contributes significantly to climate change because of the emissions of CO<sub>2</sub> due to fossil fuels and hazardous waste. Green chemistry finds solutions toers by using the Twelve Principles by decreasing toxicity, energy requirements and wastes. The Atom Economy, Carbon Efficiency, and Renewable Feedstock Utilisation are examples of such Key Performance Indicators (KPIs) that are used to measure the development and ensure compliance with the regulatory (e.g., REACH, CSRD) and decarbonisation.

Poor standardisation and high transition costs form the barrier to success; predicted investment opportunities in the circular economy became ESG investment and circular economy innovations. The implementation of KPIs as a mandatory and inseparable component of measurable and reportable systems would help transform green chemistry into a viable action plan that would render the industry synonymous with net-zero goals and sustainable growth.

**Keywords:** Green Chemistry, Key Performance Indicators (KPI), Atom Economy, Carbon accountability, Waste Reduction, Renewable Feedstock, Energy Efficiency, Regulatory Compliance (REACH,TSCA,ISO 14001)

## INTRODUCTION

### Climate Change and the chemical industry.

Modern global economy depends on the chemical industry (Kätelhön et al., 2019), the core product of which is the contribution to pharmaceuticals, agrochemicals, polymers and speciality chemicals. Still, it is a great contributor to climate change as well since it is believed that about 10-12 per cent of all industrial pollution of the world with regards to CO<sub>2</sub> is being caused by it. The energy-intensive high-intensive industry and fossil dependency (both processes and feedstock), production of highwaste and hazardous by-products (linear production models) are the main issues leading to this consequence.

As countries are constructively looking forward to ambitious decarbonisation strategies with the help of the framework schemes such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), the direction the chemical sector is taking at the moment is a direct disobedience to the global climate goal. So as to discover the compromising point between industrialisation and environmental responsibility, industry must be transformed drastically. This transition is supported scientifically by what is known as green chemistry, the science which has been described in the Twelve Principles introduced by Anastas and Warner. This set of principles encourages the design of chemical products and processes which is less toxic, use less energy and resources use as well as enhancing safety and compatibility within their environment.

Technical substitution is not the only thing that green chemistry cares about; built-in performance assessment is needed. As an illustration of this case, the Key Performance Indicators (KPIs) may be perceived as the mandatory instruments since such indicators as the atom economy, energy intensity, carbon emissions to each unit of the product, the reduction of the hazardous wastes, and the fractions of the solvents covered by the process of being taken care of are assessed.

At the same time, most ESG-compatible standards such as GRI, SASB and CSRD across the world are currently demanding Scope 1, 2, and 3 emissions to become as inclusive as they can be in regards to carbon disclosures. Such reporting systems will be enhanced with Green chemistry KPIs to increase transparency, stimulate low-carbon research and development and augment carbon reporting. To exert as broad an international impact as possible, they will need to be put into implementation at the Measurable, Reportable, and Verifiable (MRV) systems level so that green chemistry would no longer be a visionary thought experiment but an implementable and global solution to dismantling industry carbon emissions (Luis Alberto de la Torre Vivar, 2025).

## Defining Green Chemistry: Principles and Practical Relevance:

### Principles of Green Chemistry:

Green chemistry is a science which aims at the optimisation of chemical materials and processes to reduce the usage and generation of hazardous chemicals. It was created by Paul Anastas and John Warner and is informed by 12 principles of environmentally Sound innovation, aiming at encouraging environmentally responsible innovations. Some of these principles are atom economy, energy efficiency, use of renewable feedstocks, utilisation of safer solvents or reagents.

Paul Anastas and John Warner later in 1998 released the Twelve Principles of Green Chemistry (see Fig. 1.1). These postulates guide the development of new processes and chemical products, and they are written against all elements on the process life cycle, viz. raw materials, efficiency, safety, toxicity of reagents, and biodegradability. In recent years, these values have been summarised in a more convenient form: PRODUCTIVELY (Anastas & Eghbali, 2009).

## 12 Principles of Green Chemistry



(e.g., Fig. 1.1. Twelve Principles of Green Chemistry Framework).

### Practical Relevance

The principles of green chemistry may be practically and beneficially applied in numerous applications, such as in pharmaceuticals, cosmetics, electronics and even in the agricultural field. In order to minimise pollution and utilise fewer resources, and produce safer and more eco-friendly products, the industries should operate based on these principles. One can use green solvents, safe reaction conditions in synthesis, use renewable resources

in chemical synthesis, and develop biodegradable plastics; all such usages make use of green chemistry (Höfer and Bigorra, 2007). Moreover, such global issues as the problem of climate change and depletion of natural resources may be solved with the useful effect of green chemistry because it gives an opportunity to consider the process of chemical production more cyclic and more sustainable. 2. The Critical Role of KPIs in Advancing Green Chemistry:

Adoption of green chemistry is not just about a scientific venture, but it is a working venture. It is obvious how they can be done in general, but as to where to integrate them into the production systems, which can be scaled up and how to continuously assess the ways they perform, the actual problem rests. The tendency to quantify the results is important to maintain the degree of relevance, imitation and improvement of the production cycle. According to this gap, KPIs provide pragmatic and strategic principles of measuring performance. KPIs provide a systematic approach to measure green chemistry work and inefficiencies, in addition to putting a context of sustainability on their overall work. Without these efforts, there is no unity in the efforts, and efforts are not readily accessible. By incorporating KPIs in the operations procedures, companies can be assured that the concept of green chemistry is not an abstract approach but an approach that is viable, measurable and dynamic to sustainable progress in the scientific field.

KPIs create boundaries for green chemistry, which can be measured and an organisation can use to draw the changes in the environment that can point out the extent of wastefulness and communicate any advancement conveniently. Otherwise, the green chemistry theory is hypothetical and does not work after its application on a large scale or when not invoked during corporate processes. Key Performance Indicators (KPIs) are important metrics used in green chemistry to enable measurements of the progress and guarantee continuous improvement [16].

Category	KPI/Metrics	Definition and Purpose	Ideal Target
Process Efficiency	Atom Economy (%)	Fraction of atoms in the reacting substance as it is that ends as a constituent of the product. Shows effectiveness of actions.	Higher = less waste (80 percent)
	Carbon Efficiency (%)	Per cent of raw materials carbon used in the product. Reduces GHGs emission.	90% (reduces wastage of carbon)
	Process Mass Intensity (PMI)	The total quantity of materials used that are divided by a unit of product (kg/kg) the lesser = the better.	Minimize (industry-specific)
	Percent Solvent Recovery (%)	per cent of solvents that can be recycled/re-used. Lessens the wastage and costs.	70 percent (optimal closed-loop systems)
Environmental Impact	E-Factor (kg waste/Kg product)	Unit cost of wastes. The more pure = Lower.	(perfect to serve pharmaceuticals)
	CO <sub>2</sub> (e) kg climate emissions (GHG)	Production carbon footprint. Monitors decarbonization.	Shift YoY (net-0 aligned)
	Water (L/kg product) efficiency of usage	Product consumptions of water to the unit. Promotes conservation.	Reduce (industry standards are variable)
	Reduction of Toxicity (%)	Reduction percentage of hazardous chemicals (e.g. solvents, catalysts) use.	100 percent replacement (the possible cases)
Economic and Operational	Waste Reduction savings (\$)	New annual reduction in the cost of waste disposal (and additional raw materials required).	Increase YoY
	Utilisation (Renewable Feedstock %)	in % of bio-based/ recycled inputs in the production. Encourages the circle economy.	>50% (industry-independent)
	Reg Compliance Rating	Assessed on basis of Standards (e.g. REACH, TSCA). Avoids penalties.	100% compliance
Innovation & Market	Portfolio Green Products	per cent of the products that were developed using green chemistry.	YoY increase
	Science Research and Development Spending Quarta-Diura (\$)	Sustainable process/product research and development expenditures.	One tenth of the overall budgets in R&D
	Rate of Adoption by the Customer (%)	The comparisons of the green product adoption and conventional product in the market.	Increase year on year market share
Circular Economy	Recyclable /Reusable Rate (percentage)	per cent of materials recycled or reuse (i.e. catalysts, packaging).	75 percent (closed-loop target)
	Life Cycle Assessment (LCA) score	Easy environmental impact (cradle-to-grave). Guides eco-design.	Other vs. baseline

(e.g., Fig. 1.2. KPI/Metrics and there Ideal Targets).

### Measuring Environmental Impact

The key subject of the Performance Indicators (KPIs) that can be funnelled toward the establishment of the resource efficiency of a chemical process will be the following: the Atom Economy, the Carbon Efficiency and the Waste Reduction [14]. Atom Economy is quoted as a percentage value of the ratios of the reactants used in

the productive products and more than the threshold, than the wastes. Carbon Efficiency monitors the ratio of the atoms assigned to carbon atoms in the raw goods and finished goods in order to reduce green gases. Waste reduction measures gauge the formation of by-products and promote the formation of more environmentally friendly, efficient production routes.

Such KPIs enable the industries to detect their inabilities and change them to cleaner or even liquidfree (assisted by catalysis, bio-based raw materials, or non-liquid flows). Another case is that the Carbon Efficiency may be low, and then carbon sources will be replaced by renewable sources, and the level of waste will be very high; this will imply that the process has to be redesigned. These KPIs will encourage continuous change so that the chemical manufacturing is in line with the sustainability agenda goals, and it is economical.

### Promoting Sustainable Practices Through KPIs:

It is also essential when fostering sustainability across the chemical sector, and Key Performance Indicators (KPIs) are the sure way to present this order. These metrics include consumption of energy per unit of the product and the level of use of renewable resources, which helps a business estimate and enhance the sustainability of operations. An example is monitoring the rate of recovery of solvents to enable the firms to track the transition process from the use of fossil-based solvents to the use of biodegradable ones. Such KPIs not only draw attention to the efficiency of the use of resources, but they also inform decision-making processes based on the concept of the circular economy. Continuous measurement of such parameters will enable the organisation to minimally affect the surrounding environment (Lambin & Corpart,2018), decrease carbon footprints, and achieve concrete progress in the long-term targets in sustainability.

### Regulatory Compliance and Certification

One of the factors that has resulted in the adoption of green chemistry has been regulatory compliance. These important governmental agencies and international institutions, along with the U.S. Environmental Protection Agency (EPA), the European Chemicals Agency (REACH) and the ACS Green Chemistry Institute, develop some principles and guidelines that ensure that chemicals are both safe and sustainable. The Key Performance Indicators (KPIs) can especially come in handy when it comes to the enforcement of companies to run under these regulatory conditions. Between the toxicity, atmosphere emissions, waste reduction, and resource productivity measurements, the corporations can prove that they adhere to such regulatory acts as the REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) and the TSCA (Toxic Substances Control Act). Documentation of the KPI is also applicable when it comes to the practice of certification, and the same happens with ISO 14001, which refers to some good environmental management systems (O'BRIEN, 2008). Transparency in the reporting of KPIs not only has the merit of sweeping away the legal implications, but it also makes the brand seem credible, and the stakeholders are inclined towards the brand.

Industries	KPI	Impact Area	Description
Pharmaceuticals	E-Factor	Waste Reduction	Wastes are measured in terms of every unit active pharmaceutical ingredient (API).
	Atom Economy	Resource Efficiency	Follows the effectiveness with which reactant atoms are converted into final products
	Process Mass Intensity	Material Efficiency	Mass per unit of product of the materials used (less = efficient).
	Solvent Recovery Rate	Hazard Reduction	Recycled/reused % of solvents in order to reduce toxic waste.
Agrochemicals	Carbon efficiency	GHG Reduction	Retention of feedstocks retention in end products as a percentage.
	Toxicity Reduction	Environmental Safety	Substitution of toxic pesticides by those that are biodegradable.
	Renewable Feedstock%	Circular Economy	Percentage of bio-based or recycle raw materials.
Bulk Chhemicals	GHG Emissions(CO2eq/kg)	Climate Impact	Carbon impact of kilogram of product (example ethylene, polymers).
	Recyclability Rate	Waste Valorization	Recycling of materials in closed-loop.
	Energy Consumption(kWh/kg)	Energy Efficiency	Energy consumed on amount of produced item.
Consumer Goods	%Green Products	Sustainable Design	Product content made using green chemistry.
	water usage(L/kg)	Water Conservation	Liters of water used with respect to kilogram of production.
	LCA Score	Holistic Sustainability	EI score-lifecycle (cradle-to-grave).

(e.g., Fig. 1.3. KPI use in Different Industries).

## Carbon Accountability: The Next Frontier in Green Chemistry

Carbon responsibility no longer exists in the form of reporting on emissions in sustainability reporting. It has acquired a greater burden: that of ownership of the causes of emissions, development of tangible reduction strategies, and converting the heart of industrial processes to engineer out emissions altogether. Such a transition is a strategic one in the green chemistry context: instead of trying to control reaction-based carbon management, decarbonisation of molecules at the molecular scale [15].

To understand this change, one will want to look in conjunction with the classification of emissions of a scope kind:

Scope	Type of Emission	Description
Scope 1	Direct on site Emission	The organisation-owned or controlled emissions, which include fossil-fuel boilers, furnaces, chemical reactors, and any of the operations based in the facilities.
Scope 2	Indirect Energy Emission	Purchases and Consumption of energy released as emissions of electricity, steam and chilled water. These are the off-sites, but they are the direct outcome of energy usage by the organisation.
Scope 3	Value chain Emission	All that other stuff that you have indirectly through the whole value chain i.e. extraction of raw materials, logistics of suppliers, transport, use of the product and how it is treated when it is at the end of its life. This usually constitutes the highest percentage of the total amount of emitting.

(e.g., Fig. 1.4. Type of Emission).

Even though companies have a high level of mandatory reporting of Scope 1 and 2 emissions, the Scope 3 emissions form a key aspect of the total carbon footprint produced by a chemical company, with its average being above 70%. It implies that this is a significant, yet somewhat humble, subject matter of carbon accountability.

Green chemistry has a direct impact on all three scopes of emissions since it provides sciencebased, practical innovations:

### Feedstock Substitution

Among the strongest ones, it is the replacement of relative to fossil-derived inputs by renewable or captured carbon. Bio-based feedstocks and chemicals made out of CO<sub>2</sub> not only emit less in upstream Scope 3 emissions but also provide carbon circularity. By way of illustration, the substitution of petroleum-based ethylene with ethylene derived from bioethanol would reduce embedded emissions in polymers considerably.

### Process Intensification

Both scope 1 and 2 emissions are able to be reduced to a minimum by the way a chemical reaction is designed to consume minimal energy and solvent and have reduced steps. Ambient catalysis, one-pot synthesis and solvent-free processes lead to a reduction of thermal load, energy demands through the reduction of process-level emissions.

### Onsite Renewable Integration

Decarbonisation of chemical manufacturing energy can be achieved through the introduction of solar, wind, or hydrogen-based frameworks into plant installations. The green hydrogen collected in the process with the help of electrolysis and renewable energy can serve as an alternative to fossil-only produced hydrogen to produce ammonia and serve the refinery process, as well as the production of polymers. This movement will reduce the scope 2 emissions and, in the long run, achieve energy resiliency (Singh, Anipeddi Manjusha and Lal, 2024).

## Molecular Design for Zero-Carbon Pathways

Green chemistry [22] goes ahead to accommodate the science of sorting the molecules and reactions in a way that they do not leave a carbon footprint. These also involve the requirement of the benign starting materials and carbon-sequestering routes and intermediates that are also recycled back into nature without emitting CO<sub>2</sub>. Emission reduction is definitely not the right KPI in this regard, but the design is aimed at the removal of emissions.

Hence, the carbon accountability could not have been a reporting issue, but it was a design issue. The way through which a response to such menace can be achieved is already in the hands since the tools that green chemistry offer are the very ones which are required to ensure that carbon responsibility is ensured on all levels of chemical innovation, whether it is raw material, intermediate product or final product. In this manner, the chemical industry will be able to transition into the leadership phase since it would prove to be one of the most important agents of decarbonisation as a trend in the world.

## Challenges and Opportunities in Implementing KPIs for Green Chemistry

It would be necessary to adopt effective Key Performance Indicators (KPIs) of sustainability in chemical production using adherence to the concept of green chemistry [19]. These are the best indicators to be of assistance in quantifying the environmental performance, processing efficiency and compliance with this regulation. However, despite the increasing trend of sustainable innovation, there exist enormous challenges to the implementation of standardised KPIs in and among the chemical sector all over the world.

### Challenges

#### Lack of Global Standardisation

Among the most evident challenges, there is a lack of a common framework for the green chemistry KPIs. The requirements and sustainability benchmarks that differ according to various jurisdictions include the Corporate Sustainability Reporting Directive (CSRD) in the European Union, climate-related disclosure rules by the U.S. Securities and Exchange Commission (SEC), and the framework by the International Sustainability Standards Board (ISSB). This has led to attempting consistent performance measurement, and the extent to which this can be measured is not achievable because of this fragmentation.

#### Cost Constraints in Transitioning Legacy Systems:

Old chemical plants are usually preoccupied with factors of throughput and cost-efficiency to the detriment of being kinder to the environment. The shift to low-carbon or renewable-based processes comes at great costs as new catalysts and a renewable supply chain of feedstocks are involved in addition to intensified processes. Moreover, the implementation of monitoring systems capable of the measurement of atom economy, E-factors and Scope 1-3 emissions is also not a straightforward practice but costly, in particular, to SMEs (waziri, 2022).

#### Inadequate Scope 3 and End-of-Life Data

Although Scope 1 and Scope 2 are more measurable by measuring direct energy and material flows, Scope 3 covers the extraction of raw materials upstream and the use of products downstream and other logistics, which are very hard to quantify. This is aggravated by the emergence of data availability gaps and weak traceability in cross-level supply chains. Also, the end of life of the chemical products is still technically problematic, thus hindering the creation of good lifecycle-based KPIs[5].

### Opportunities

#### Emerging Regulatory Drivers

The green chemistry KPIs are being fueled by the recent policy tools. Such real-world regulations are already being integrated (or planned), including CSRD, SEC climate risks, and ISSB reporting, which include

sustainability indicators in mandatory reporting. These types of instruments are more concerned with the transparency of environmental performance, and they are becoming more prone to KPIs, which are energy intensity of an organisation, renewable feedstock percentage and carbon density per functional unit (Wachira, Berndt and Romero, 2019).

### **Investor-Led Accountability**

The latter is the financial sector and its provision of capital, placing a focus on ESG, which is performing under much pressure. Asset managers and institutional investors are starting to rank a chemical company based on its sustainability disclosure policies [4]. Failure to provide reports with the main KPIs may lead to delisting of stock in ESG funds and even loss of confidence by shareholders. Good KPI reporting, on its part, results in the increased ESG rating of a firm, the improvement of relations with the investor, and the opportunity to realise the instrument of sustainable finance.

### **Strategic and Competitive Advantages**

First-mover advantages are associated with the benefits of early green chemistry KPIs [20]. The businesses that adopt strict measurement systems have an advantage in responding much earlier to the change of policy, they can anticipate market demands, and they have an advantage in positioning their products based on authentic green performance factors. Decision making conducted based on KPIs is helpful for internal innovation as well, and it lets R&D concentrate efforts on lowcarbon processes, closed-loop systems, as well as safer substitutes for chemicals.

## **CONCLUSION**

### **From Green Vision to KPI-Driven Action**

On the one hand, green chemistry, which used to be treated once as a certain form of progressive ideal, has now evolved into a scientific and strategic necessity in the global strategy of confronting climate change [3]. As much as the chemistry industry is among the largest emitters and a core form of industrial value chain, it has two functions, and they are the accountability of the past influence and the ability to lead the change towards sustainability. Still, this transition cannot be created on visions; it must be measurable, as information-based systems, which integrate the notion of sustainability into the heart of chemical creative activities.

This is the reason the Key Performance Indicators (KPIs) can make a difference. According to examples, among the metrics, there is atom economy, lifecycle carbon intensity, reduction of hazardous wastes, and utilisation of renewable feedstocks, which are not just an application of reporting tools, but also the application of tools. KPIs in mixtures with ESG framework, regulation (e.g. CSRD, SEC and ISSB), and scope 1-3 carbon reporting will assist the chemical manufacturer to move the sustainability discussion to meaningful active change (Zhang and Zhou, 2024).

Carbon metrics are no longer on the fringe—they form the core of the reengineering of the chemical processes to meet net-zero goals. It requires integration of emissions control at the individual molecule stage of operations, through intensification of processes, elimination of solvents, restructuring feedstocks, and in so doing creating the reality of a circle of end-of-life planning. In this regard, KPIs become not merely a means of compliance but that of innovation and strategic advantage.

The chemical industry is at a crossroads where international markets and regulatory bodies, and the flow of investment, are already beginning to gravitate towards sustainable performance. The business of sustainable manufacturing will be determined by individuals who can lead in the measurable activities according to science, according to policy, and be open to the stakeholders. Through that, they will not only be in a position to guarantee against the hazards of climate change, but will also redefine industry brilliance in the 21st century [10].

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#### Ethics Statement

This study did not involve human participants, animals, or the use of sensitive personal/biological data.

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The data supporting this study are available in the references cited. Further details may be provided by the corresponding author upon reasonable request.