Reaching for Green Chemistry

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Abstract

This article explores the relationships between the principles of green chemistry and chemicals legislation, focusing on the REACH regulation of the European Union. Based on studies of the regulation and its implementation, as well as of research literature in the field, we evaluate if and how REACH promotes green chemistry. While both REACH and green chemistry aim for innovation and environmental and health protection, there are gaps between environmental goals and the green chemistry potential on the one hand, and the regulatory demands on the other. Despite some provisions in REACH that promote generation of knowledge and data, as well as phase-out of hazardous substances, REACH in general is a weak driver of green chemistry at present. REACH fosters less hazardous chemical synthesis and safer chemicals, but the requirements are often not stringent enough and the implementation processes are very slow and resource consuming. In addition, most green chemistry principles, including on renewable feedstocks, are not promoted by REACH. However, it would be in line with the multiple aims of REACH to promote green chemistry through e.g. higher demands on data generation, a broader inclusion of articles, stricter demands on substances and substitution, as well as a set of other amendments that promote green chemistry. The article provides a number of recommendations on how to better reach for green chemistry, and contributes to the understanding of how gaps between environmental goals and industrial practice can be better bridged by legislation, in this case eventually promoting a non-toxic environment.

Keywords: chemicals policy; environmental goals; green chemistry; non-toxic environment; REACH regulation; substitution

Introduction

Environmental goals for chemical substances are generally not achieved on global, regional and national levels[1]. Despite increasing efforts over time, chemicals policy principles and instruments, as well as their implementation, are still generally insufficient in relation to existing public objectives[2]. Governmental agencies are confronted with huge challenges, from lack of knowledge and data gaps[3] to high burden of proof requirements in law[4]. The two basic components of a chemical risk assessment – intrinsic properties of

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1 UNEP (2019) *Global Chemicals Outlook II*. Nairobi: United Nations Environment Program (UNEP); EEA (2018) *Achieving EU's key 2020 environmental objectives slipping away*. Copenhagen: European Environment Agency (EEA); SEPA (2019) *Fördjupad utvärdering av miljömålen 2019*. Stockholm: Swedish Environment Protection Agency (SEPA).

2 Karlsson M and Gilek M (2018) Management of Hazardous Substances in the Marine Environment. In: Salomon M and Markus T (eds.) *Handbook on Marine Environment Protection: Science, Impacts and Sustainable Management*. Dordrecht: Springer.

3 Kortenkamp A and Faust M (2018) Regulate to reduce chemical mixture risk. *Science* 361, 224–226.

4 Karlsson M and Gilek M (2019) Mind the Gap: Coping with delay in environmental governance. *AMBIO*. Available at: https://doi.org/10.1007/s 13280-019-01265-z.

substances and exposure conditions – are seldom known, but regulatory agencies are still generally required to prove the presence of unacceptable risks before more stringent risk management measures can be implemented. Chemicals policy is thus reactive and not in line with the precautionary principle[5]. Moreover, many companies also struggle to control chemical risks, but safety measures are hampered for several reasons, not least due to complex global supply chains, where production and consumption often take part in different regions, with different policies[6]. Placing requirements on chemicals in goods assembled by products from a number of different countries and various production lines is challenging. At the same time, many chemicals are indispensable for welfare, as well as for environmental protection, making the need for development of less hazardous substances obvious. In order to improve the achievement of environmental and health objectives, in parallel with continued use of chemical substances that are essential in society, chemicals policy and substance innovation should therefore preferably be mutually supportive and promote sustainable development, including the goal of a non-toxic environment[7]. This article explores that ambition and evaluates chemicals policy in relation to one strategy of relevance in this context – green chemistry.

Green chemistry aims at designing better products, processes, materials and molecules from a sustainability point of view[8], of relevance for research, management and policy[9]. Although there is substantial potential in green chemistry[10], a lack of regulatory standards[11] and the common complexity of global supply chains[12] present implementation challenges. Chemicals policy can potentially counteract these challenges for green chemistry, as regulation has done in other cases[13], in line with the hypothesis that well-designed environmental policies can trigger innovation and thereby enhance competitive advantage[14]. This study takes green chemistry as a starting point and investigates chemicals policy and in particular if and how legislation

[5] Karlsson M (2010) The Precautionary Principle in EU and U.S. Chemicals Policy: A Comparison of Industrial Chemicals Legislation. In: Eriksson J, Gilek M and Rudén C (eds.) *Regulating Chemical Risks: European and Global Challenges*. Dordrecht: Springer.

[6] Börjeson N (2017) *Toxic Textiles. Towards Responsibility in Complex Supply Chains*. Doctoral Dissertation, Södertörn University. Stockholm: Elanders; Fransson K and Molander S (2013) Handling chemical risk information in international textile supply chains. *Journal of Environmental Planning and management* 56, 345–361.

[7] The goal is part of the Swedish environmental objectives system, and is in the EU pipeline; see e.g. SEPA (2019) op. cit.

[8] Anastas PT and Warner JC (1998) *Green Chemistry: Theory and Practice*. Oxford: Oxford University Press; Linthorst JA (2010) An overview: origins and development of green chemistry. *Foundations of Chemistry* 12, 55–68.

[9] Sjöström J (2006) Green chemistry in perspective. *Green Chemistry* 8, 130–137.

[10] Manley JB, Anastas PT and Berkeley WC (2008) Frontiers in Green Chemistry: meeting the grand challenges for sustainability in R&D and manufacturing. *Journal of Cleaner Production* 16, 743–750.

[11] Iles A (2008) Shifting to Green Chemistry: The Need for Innovations in Sustainability Marketing. *Business Strategy and the Environment* 17, 524–535.

[12] Fennelly T and Lustglass B (2015) *Advancing Green Chemistry: Barriers to Adoption and Ways to accelerate Green Chemistry in Supply chains*. A Report for the Green Chemistry & Commerce Council. Osseo: T Fennelly & Associates, Inc.

[13] Eder P and Sotoudeh M (2000) *Innovation and clean technologies as a key to sustainable development: the case of the chemical industry*. Brussels: European Commission; Karlsson M (2006) The Precautionary Principle, Swedish Chemicals Policy and Sustainable Development. *Journal of Risk Research* 9, 337–360; Tuncak B (2013) *Driving innovation. How stronger laws help bring safer chemicals to market*. Washington: CIEL; Boström M and Karlsson M (2013) Responsible procurement, complex product chains and the integration of vertical and horizontal governance. *Environmental Policy and Governance* 23, 381–394.

[14] Porter M and van der Linde C (1995) Towards a New Conception of the Environment-Competitiveness Relationship. *Journal of Economic Perspective* 9, 97–118; Iles (2008) op. cit.; Ambec S, Cohen AM, Elgie S et al. (2013)

on chemicals risk management promotes the implementation of green chemistry, or whether there exists an untapped regulatory potential or even regulatory barriers. In doing so, we aim to identify and present a set of science-based policy recommendations, which in the long run may foster a non-toxic environment.

The examination is focused on the EU, a region in which chemicals policy is considered to be at the forefront[15]. We restrict the evaluation to the most central piece of EU chemicals policy, namely the 2006 REACH regulation on industrial chemicals[16], which has been considered both comparatively ambitious[17] and internationally trend-setting[18], albeit not everywhere[19], making it a suitable study object in this context. Having been into force for more than a decade, the REACH regulation has also recently been officially reviewed, which provides sources of experience for our study, as well as opens for giving input in case of future policy development.

Other central pieces of EU chemicals regulation, or EU environmental policy at large, are not studied in this specific article[20]. Our evaluation of REACH departs from a set of commonly recognised core principles for green chemistry, which leads over to a discussion on how REACH potentially can be developed to better promote green chemistry. This improves the understanding of how chemicals policy in a broader sense can help green chemistry to play a more prominent role for achieving environmental goals, an area so far being poorly studied[21]. The study is based on an examination of the REACH regulation as such, on public documents and other sources and literature focusing on REACH implementation, as well as on research literature on green chemistry and chemicals policy and law in general.

In the next two sections, we briefly describe the basic principles of green chemistry and the REACH regulation, respectively. This is followed by the main result section, in which we evaluate the REACH regulation in relation to the principles. The article ends with a discussion with recommendations regarding future chemicals legislation.

The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Review of Environmental Economics and Policy* 7, 2–22; Fennelly and Lustglass (2015) op. cit.

15 Bergkamp L (ed.) (2013) *The European Union REACH Regulation for Chemicals: Law and Practice*. Oxford: Oxford University Press; Karlsson and Gilek (2018) op. cit.

16 Regulation (EC) 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. *Official Journal of the European Union L* 396:1–849.

17 GAO (2007) *Chemical Regulation. Comparison of U.S. and Recently Enacted European Union Approaches to Protect against the Risks of Toxic Chemicals*. Report 07-825. Washington: United States Government Accountability Office (GAO); Wilson MP and Schwarzman MR (2009) Toward a New U.S. Chemicals Policy: Rebuilding the Foundation to Advance New Science, Green Chemistry, and Environmental Health. *Environmental Health Perspectives* 117, 1202-1209; Swedish Chemicals Agency (2015) *Developing REACH and improving its efficiency – an action plan*. Report 2-15. Sundbyberg: Swedish Chemicals Agency; Karlsson and Gilek (2018) op. cit.

18 Uyesato D, Weiss M, Stepanyan J et al. (2013) REACH's impact in the rest of the world. In: Bergkamp op. cit.

19 Botos A, Graham JD and Illés Z (2018) Industrial chemical regulation in the European Union and the United States: a comparison of REACH and the amended TSCA. *Journal of Risk Research* 22, 1187–1204.

20 Evidently, other parts of EU law are also central for green chemistry, for example the Industry Emission Directive, but we do not analyse these here. See however Führ M, Schenten J, Kleihauer S et al. (2018) *Integrating "Green Chemistry" into the Regulatory Framework of European Chemicals Policy*. Final draft. Darmstadt: Sonderforschungsgruppe inter-disziplinäre Institutionenanalyse.

21 However, see ibid., as well as Choudhury AK (2013) Green chemistry and the textile Industry. *Textile Progress* 45, 3–143.

Green Chemistry

Green chemistry[22] is a pollution prevention initiative that aims to promote sustainable development through designing chemical products and processes in a way that reduces or eliminates chemical risks and the use and generation of hazardous substances. It is a strategy that is increasingly applied since two decades, with specific journals and research and development programs[23], focusing on solving problems related to chemical pollution at the molecular level[24], but it is also relevant for management and policy[25]. Advances in green chemistry address risks in factories and products related to the presence of hazardous substances, energy and the use of fossil fuels, as well as management and policy. Antifouling boat paint without tin, fire extinguishers without freons, dry cleaning without perchloroethylene, and lumber without arsenic are examples of green chemistry solutions[26]. These efforts circle around 12 core principles of green chemistry, originally developed by Paul Anastas and John Warner[27], which outline what is considered to constitute a greener chemical, process, or product[28]:

[22] Sometimes the concept 'sustainable chemistry' is used (e.g. Umweltbundesamt (2009) *Nachhaltige Chemie*. Dessau-Rosslau: Umweltbundesamt), but it is vague and less frequently used (Linthorst (2010) op. cit).
[23] See for example the journals 'Current Opinion in Green and Sustainable Chemistry' (Elsevier), and 'Green chemistry' (Royal Society of Chemistry), as well as the program 'SusChem', available at: http://www.suschem.org/about (accessed 18/11/2019).
[24] Anastas and Warner (1998) op. cit.
[25] Sjöström (2006) op. cit.
[26] Manley JB, Anastas PT, Cue BW (2008) Frontiers in Green Chemistry: meeting the grand challenges for sustainability in R&D and manufacturing. *Journal of Cleaner Production* 16, 743–750.
[27] Anastas and Warner (1998) op. cit.
[28] Anastas PT and Eghbali N (2010) Green Chemistry: Principles and Practice. *Chemical Society Reviews* 39, 301–312.

Table 1. 12 Principles of Green Chemistry[29]

1. **Prevention**: It is better to prevent waste than to treat or clean up waste after it has been created ('an ounce of prevention is worth a pound of cure').
2. **Atom Economy**: Synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product, in order to avoid by-products.
3. **Less Hazardous Chemical Syntheses**: Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. **Designing Safer Chemicals**: Chemical products should be designed to affect their desired function while minimising their toxicity.
5. **Safer Solvents and Auxiliaries**: The use of e.g. solvents should be rendered unnecessary wherever possible and these should be innocuous.
6. **Design for Energy Efficiency**: Energy requirements of chemical processes should be recognised for their environmental and economic impacts and should be minimised.
7. **Use of Renewable Feedstocks**: A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **Reduce Derivatives**: Unnecessary derivatisation (e.g. temporary modification of physical/chemical processes) should be minimised or avoided, since this require additional reagents and can generate waste; natural processes are preferable.
9. **Catalysis**: Catalytic reagents are superior since they help to reduce energy needs, increase efficiency and reduce by-products.

[29] After ibid.

10. **Design for Degradation**: Chemical products should be designed so that, at the end of their function, they break down into innocuous degradation products and do not persist in the environment.
11. **Real-time Analysis of Pollution Prevention**: Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. **Inherently Safer Chemistry for Accident Prevention**: Substances and the form of a substance used in a chemical process should be chosen to minimise the potential for chemical accidents, including releases, explosions, and fires.

These principles are to be seen as guiding tools for producers and other operators who aim for achieving less harmful substances, mixtures and products, and they may be applied differently in different contexts, even though applying all of them at the same time might be difficult to achieve[30]. The principles are also highly relevant for policy-makers, who develop regulatory frameworks that aim for chemicals safety, as well as for agencies that implement chemicals legislation. In many respects, implementing the principles promotes the goal of a non-toxic environment, which includes phasing out substances that may cause chronic toxicity (e.g. carcinogenic substances) or that may be persistent (and hence are globally dispersed) and bioaccumulative (and therefore risk to be taken up by humans and other organisms).

Whereas development and implementation of additional or more stringent chemicals regulation might not only stimulate innovation, but also impose additional costs on companies[31], the principles of green chemistry aim at enabling win-win outcomes in terms of both the environment and the economy. Chemicals legislation that applies these principles is therefore of potential importance from not only an environmental goal perspective, but also from business point of view. To what extent REACH succeeds in doing so is evaluated after the next section, which describes and comments on the regulation.

The EU REACH Regulation

EU chemicals policy is still developing, after its emergence in the 1960s, and constitutes a legal web that today regulates production, import and use of chemical substances. Companies must comply with a broad set of laws concerning environment and public health, spanning from softer tools such as classification and labelling to comparatively strict restrictions of certain substances[32]. The legal centrepiece is the referred REACH regulation, which has been considered to be a comparatively ambitious chemicals law[33].

The REACH regulation entered into force in 2007 and replaced a number of previous EU

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30 Blum CFT and Stolzenberg H-C (2016) Sustainable chemistry: Strategies and initiatives of the German Environment Agency (UBA). Presentation at the *Green and Sustainable Chemistry Conference* in Berlin, 3–6 April 2016.

31 European Commission (2015) *Monitoring the Impacts of REACH on Innovation, Competitiveness and SMEs. Final Report*. Brussels: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, European Commission.

32 See overviews in e.g. Bergman P (2012) *Bättre EU-regler för en giftfri miljö – rapport från ett regeringsuppdrag*. Report 1-12. Sundbyberg: Swedish Chemicals Agency; Biedenkopf K (2018) Chemicals: Pioneering Ambitions with External Effects. In: Adelle C, Biedenkopf K and Torney D. (eds.) *European Union External Environmental Policy. The European Union in International Affairs*, pp. 189–208. London: Palgrave Macmillan.

33 Wilson and Schwarzman (2009) op. cit.; Karlsson M (2010) op. cit.; Bergkamp (2013) op. cit.; Swedish Chemicals Agency (2015) op. cit.; Filipec O (2017) *REACH Beyond Borders – Europeanization Towards Global Regulation*. Dordrecht: Springer. For overviews see also Nilsson A (2010) Reach och hållbar kemikaliehantering. In: Ebbesson J and Langlet D (eds.) *Koll på kemikalier? Rättsliga förändringar, möjligheter och begränsningar*. Uppsala: IUSTUS.

laws that among other things differentiated between so-called existing and new substances, the former being hardly controlled with respect to health and the environment. REACH aims to promote a high level of protection of human health and the environment, alternative methods to assess hazards, as well as free movement on the EU internal market, enhanced competitiveness and innovation (Article 1[34]). The market orientation of REACH is founded on the treaty and expresses the EU harmonisation ideal, which also means that the regulation falls into the category, in e.g. the European Commission, of industry affairs and growth issues, rather than the environment[35]. REACH includes four key building blocks: registration, evaluation, authorisation and restriction of chemicals. It also regulates information flow in supply chains, including a consumer's right to information, as well as confidential business information[36]. A specific agency, the European Chemicals Agency (ECHA), is set up for governing the regulation (Articles 75–111) in parallel with the European Commission and the EU Member States.

The provisions in the registration block promote a "no data, no market" principle for the substances and mixtures that are targeted by REACH (Article 5). Under certain conditions, the same applies to substances in "articles" (i.e. products on the market), if an article is intended to release a substance under normal and foreseeable use, provided a certain total quantity per year, or if the article contains certain levels of particularly harmful substances (Article 7). For previously existing (so-called phase-in) substances and mixtures, a gradual transition period has recently passed. For example, requirements on producers and importers applied from 2010 for substances being toxic (carcinogenic, mutagenic, reproductive toxins or very toxic to aquatic organisms), in quantities over 1 tonne, or manufactured or imported in high quantities (above 1000 tonnes per year and producer or importer), and from 2018 for substances in quantities between 1 and 100 tonnes (Article 23). The current (November 2019) number of REACH registrations is 96761 (dossiers), of which 22468 are unique substances[37]. For substances in quantities above 10 tonnes, a comparatively comprehensive Chemical Safety Report (describing e.g. intrinsic substance properties, exposure scenarios and management recommendations) is required (Article 14), while for the 1–10 tonne interval, a more rudimentary Technical dossier (with basic data) is compulsory (Article 10). Despite the aims of REACH, much falls outside the scope of the regulation, such as polymers and substances in lower quantities (e.g. Article 2), and chemicals assumed to be sufficiently covered by other laws (such as pesticides). In addition, data requirements are often insufficient in relation to the risk management objectives of the regulation[38], registration

34 REACH references in this article are made to the consolidated version of REACH of July 2, 2019 (02006R1907 — EN — 02.07.2019 — 041.001 — 1), available at: https://eur-lex.europa.eu/legal-content/en/TXT/PDF/?uri=CELEX:02006R1907-20190702&qid=1565790018151&from=EN (accessed 18/11/2019).

35 The original basis for REACH is article 95 in the Treaty Establishing the European Community, presently replaced by article 114 in the Treaty on the Functioning of the EU.

36 The following overview focuses on the key elements of REACH in relation to the aims of the present article; for more comprehensive descriptions or detailed analysis, see e.g. Karlsson (2010) op. cit. and Bergkamp (2013) op. cit.

37 See the database at the European Chemicals Agency (ECHA): https://echa.europa.eu/information-on-chemicals/registered-substances (accessed 18/11/2019).

38 Lahl U and Zeschmar-Lahl B (2013) Risk based management of chemicals and products in a circular economy at a global scale (risk cycle), extended producer responsibility and EU legislation. *Environmental Sciences Europe* 25:3; Rudén C and Hansson SO (2010) Registration, Evaluation, and Authorization of Chemicals (REACH) is but the first step – how far will it take us? Six further steps to improve the European chemicals legislation. *Environmental Health Perspectives* 118, 6–10.

requirements are often not adequately met[39], and the transparency of data is often limited[40].

In the evaluation block, the ECHA carries out a compliance check of registration dossiers (Article 41) and evaluates any existing animal testing proposals (Article 40), whereas EU Member States may evaluate risks associated with registered substances (Article 45). The compliance check targets a low percentage of the registered substances but still reveals a striking non-compliance with legal requirements[41]. If the evaluation shows that e.g. more information is needed or that there are reasons for concern, further data can be required (Articles 41, 50). The evaluation follows a so-called Community Rolling Action Plan (Article 44) that so far lists 375 substances, of which conclusions have been finalised for 105, i.e. for less than 1 percent of all registered substances[42]. For several of these, the conclusion is drawn that regulatory follow up is needed[43], which may eventually lead to authorisation or restriction requirements.

When it comes to the authorisation block, the focus is placed on 'substances of very high concern' (SVHCs) (Article 55), i.e. substances that may have serious effects on human health or the environment. The criteria for a SVHC are detailed in the regulation, and SVHCs include substances that are carcinogenic, mutagenic or toxic for reproduction (CMRs), persistent, bioaccumulative and toxic (PBT), very persistent and very bioaccumulative (vPvBs), or that cause equivalent concern (Article 57). Such substances are to be placed on a 'candidate list' (CL) (Article 59), from which a prioritisation is to be made before a substance, after a specific decision (Article 58), ultimately may be targeted for authorisation. Once listed (Annex XIV), importers or downstream users wanting to use a substance for a specific purpose must seek authorisation, which may be limited to certain uses and articles, but this does not automatically apply when a substance is present in an imported article[44], which illustrates that REACH is not set up in order to control chemicals in global supply chains[45]. Moreover, an authorisation in an individual case generally presumes that risks to health and the environment are 'adequately controlled', except for SVHCs that are PBT, vPvB or CMRs, where a threshold cannot be determined. In the latter case – or when control is not adequate – authorisation depends on the risks being outweighed by socioeconomic benefits and on a lack of available substitutes. Placing substances on the CL or in Annex XIV, as well as authorisation processes, are often preceded by time and resource consuming anal-

39 European Commission (2018a) *Commission Staff Working Document accompanying "Commission General Report on the operation of REACH and review of certain elements. Conclusions and Actions." COM(2018) 116 final*. SWD(2018) 58 final. Part 1/7. Brussels: European Commission; UBA (2015) *REACH Compliance: Data Availability of REACH Registration. Part 1: Screening of chemicals > 1000 tpa*. Dessau-Roßlau: Umweltbundesamt (UBA); UBA (2018) *REACH compliance: Data availability in REACH registrations. Part 2: evaluation of data waiving and adaptations for chemicals > 1000 tpa*. Dessau-Roßlau: Umweltbundesamt (UBA).

40 Ingre-Khans E, Ågerstrand M, Beronius A et al. (2016) Transparency of chemical risk assessment data under REACH. *Environmental Science: Process and Impacts* 18, 1508–1518.

41 ECHA (2018) *Evaluation under REACH: Progress Report 2017. 10 years of experience*. Helsinki: European Chemicals Agency (ECHA).

42 See ECHA at: https://echa.europa.eu/information-on-chemicals/evaluation/community-rolling-action-plan/corap-table (accessed 18/11/2019).

43 Ibid; see further in the various documents for substances with evaluations that are concluded.

44 Molander L and Rudén C (2012) Narrow-and-sharp or broad-and-blunt. Regulations of hazardous chemicals in consumer products in the European Union. *Regulatory Toxicology and Pharmacology* 62, 523–531; Molander L, Breitholz M, Andersson PL et al. (2012) Are chemicals in articles an obstacle for reaching environmental goals? Missing links in EU chemical management. *Science of the Total Environment* 435–436, 280–289.

45 Boström and Karlsson (2013) op. cit.

ysis and inefficient negotiations, often involving lengthy discussions in e.g. a Committee for Risk Assessment and a Committee for Socioeconomic Analysis (Articles 60, 64). Furthermore, the substitution requirements (Articles 55, 60) in the regulation are weak and only apply under specific conditions; for example, a substitution plan is to be developed only if a safer alternative is identified by the applicant, meaning that the burden of proof for substitution generally rests on the regulators[46].

Since the ECHA, Member States and the European Commission regularly negotiate and often disagree on how to assess and interpret substance properties and risks[47], the practice of REACH does not guarantee that a substance meeting the stipulated criteria is authorised as intended[48]. All in all, a number of different problems and challenges with the authorisation requirements and processes in the REACH regulation have been pointed out by researchers, as well as the European Commission and competent agencies in different Member States[49]. Currently (November 2019), the CL contains 201 substances[50], including some bromated flame-retardants and phthalates, and 43 substances[51] have been placed on the authorisation list (REACH Annex XIV). The contrast to the 1400 substances that the European Commission initially estimated would be targeted for potential authorisation is striking[52]. Still, the REACH authorisation requirements have meant that several companies have improved their control of SVHCs and that substitution in a number of cases most likely has been generally promoted[53].

Under the restriction block, EU Member States, the ECHA or the European Commission may call for measures first when there is a sufficiently well proven 'unacceptable risk' to the environment or to human health, irrespective of whether the substance in question is subject to registration demands or not (Article 68). However, there are no uniform criteria for what

46 Karlsson (2010) op. cit.; Hansson SO, Molander L and Rudén C (2011) The substitution principle. *Regulatory Toxicology and Pharmacology* 59, 454–460; Swedish Chemicals Agency (2015) op. cit.; Tickner J and Jacobs M (2016) *Improving the Identification, Evaluation, Adoption and Development of Safer Alternatives: Needs and Opportunities to Enhance Substitution Efforts within the Context of REACH*. Lowell: Lowell Center for Sustainable Production University of Massachusetts.

47 For example, the results from different risk assessments for the same substance may differ significantly; see e.g. Beronius A, Rudén C, Håkansson H et al. (2010) Risk to all or none? A comparative analysis of controversies in the health risk assessment of bisphenol A. *Reproductive Toxicology* 292, 132–146.

48 Karlsson (2010) op. cit.; Swedish Chemicals Agency (2015) op. cit.

49 Molander L and Rudén C (2012) op cit.; Bergkamp L and Herbatschek N (2014) Regulating Chemical Substances under REACH: The Choice between Authorization and Restriction and the Case of Dipolar Aprotic Solvents. *Review of European Community & International Environmental Law* 23, 221–245; Gabbert S, Scheringer M, Ng CA et al. (2014) Socio-economic analysis for the authorisation of chemicals under REACH: A case of very high concern? *Regulatory Toxicology and Pharmacology* 70, 564–571; Swedish Chemicals Agency (2015) op. cit.; Klika C (2015) The Implementation of the REACH Authorisation Procedure on Chemical Substances of Concern: What Kind of Legitimacy? *Politics and Governance* 3, 128–138; Gabbert S, and Hilber I (2016) Time matters: A stock-pollution approach to authorisation decision-making for PBT/vPvB chemicals under REACH. *Journal of Environmental Management* 183, 236–244; European Commission (2018b) *Commission Staff Working Document accompanying "Commission General Report on the operation of REACH and review of certain elements. Annex 4." COM(2018) 116 final*. SWD(2018) 58 final. Part 5/7. Brussels: European Commission.

50 See ECHA at https://echa.europa.eu/candidate-list-table (accessed 18/11/2019).

51 See ECHA at https://echa.europa.eu/authorisation-list (accessed 18/11/2019).

52 European Commission (2001) *Strategy for a future Chemicals Policy. White Paper*. COM (2001)88. Brussels: European Commission.

53 CSES, RPA and Ökopol (2015) *Monitoring the Impacts of REACH on Innovation, Competitiveness and SEMs. Final Report*. Brussels: European Commission; Mistry R, Moerman H, Novak A et al. (2017) *Impacts of REACH Authorisation. Final Report*. Brussels: European Commission; European Commission (2018b) op. cit.

makes a risk 'unacceptable'[54], and decisions shall consider socio-economic impacts, including the availability of alternatives (Article 68). As for the authorisation block, the restriction process is complex and often time and resource consuming (Articles 70–73), meaning that the efficiency is low, also when the scientific evidence of problems or risks is strong[55]. The burden of proof rests strongly on the public side in this case. Consequently, as few as 70 entries[56] (November 2019) in the restriction annex (XVII) of REACH show all the restriction decisions that have been adopted for a substance, a group of substances or a substance in a mixture, which may also apply to articles containing the substance, rarely also including imported ones[57].

In addition to the four basic building blocks outlined above, REACH contains a number of provisions that focus on improving the flow of information along supply chains. One example is that suppliers of articles containing substances on the CL (above 0.1 weight-per cent in any specific component of the article[58]) must provide information business to business on the presence of the substance and on how to safely use the article in question (Article 33:1). Moreover, consumers have the right to receive free information within 45 days about whether a SVHC is present (above 0.1 weight-per cent) in an article for sale (Article 33:2). These various stipulations improve the access to data. Conversely, the provisions in REACH on confidential business information partly restrict the right to request certain data (e.g. Article 118).

Finally, REACH sets out a number of review mechanisms (see e.g. Article 138) and the European Commission was obliged to carry out an initial analysis after five years, and a major review after ten years, which was finalised in 2018. In the former, clear improvements of EU chemicals risk management, compared to previous chemicals legislation, were identified, but significant shortcomings were also shown[59]. The recent, comprehensive, review[60] concluded that REACH has led to improved data along supply chains and safer products for consumers, workers and the environment, including through banning and substituting certain hazardous substances, but also that further measures need to be taken to e.g. improve the quality of data and simplify various processes[61]. The review is now a target for debate and dialogue between the various EU institutions and concerned stakeholders, and it remains to be seen what the incoming European Commission will conclude on the topic[62].

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[54] An elaboration on this can be found in Hansson SO and Rudén C (eds.) (2005) *Better Chemicals Control Within REACH*. Stockholm: KTH Royal Institute of Technology.

[55] Karlsson (2010) op. cit.; Bergkamp and Herbatschek (2014) op. cit.; Swedish Chemicals Agency (2015) op. cit.; Goldenman G, Holland M, Lietzmann J et al. (2017) *Study for the strategy for a non-toxic environment of the 7th Environment Action Programme*. Final Report. Brussels: European Commission; European Commission (2018b) op. cit.

[56] See ECHA at: https://echa.europa.eu/substances-restricted-under-reach (accessed 18/11/2019).

[57] The total number of restrictions in the EU over time is higher; the figure here refers to decisions under REACH since it was enacted.

[58] The judgement of the European Court of Justice, case C-106/142 (9/10 2015) clarified the scope of these provisions.

[59] See e.g. European Commission (2013) *Commission Staff Working Document General Report on Reach. SWD(2013)25. FINAL*. Brussels: European Commission.

[60] The various review documents are accessible at: https://ec.europa.eu/growth/sectors/chemicals/reach/studies_en (accessed 18/11/2019).

[61] See the summary of the European Commission (2018): "Ten years of REACH: making chemicals safer for consumers, workers and the environment" at: http://europa.eu/rapid/press-release_IP-18-1362_en.htm.

[62] Beyond the references above to the European Commission (2018a; 2018b), it remains outside the scope of this article to describe details of the review, and to elaborate on possible outcomes.

Evaluating REACH in Relation to Green Chemistry

Green chemistry has developed into a broad framework that covers several dimensions, from molecules to management. However, little research is so far linking green chemical design to policy and law, which justifies the focus of this article, namely, to evaluate REACH in relation to the referred twelve principles of green chemistry. The approach we take belongs to what can be labelled "law reform research", which in our case implies interdisciplinary applied research about the law, aiming for identifying potential inefficiencies and related solutions, based on doctrinal methodology with deductive reasoning[63]. In the following, we evaluate whether the 12 principles of green chemistry (which thus are used as criteria for the evaluation), one by one, are expressed in or promoted by REACH (which is the object that is evaluated)[64]. This is done by focusing on the regulatory text as such, as well as the state of implementation and the doctrine referred to in the previous section. The evaluation constitutes the basis for our discussion and recommendations.

The first principle, *prevention*, might seem quite general and the topic has been on the environmental policy agenda for a long time, but in the context of green chemistry, waste is to be reduced by improving chemical synthesis, which is more specific than conventional waste prevention. One indicator sometime used here is the 'E-factor', measuring the weight of waste per kilogram of the desired product, and the synthesis of ethylene dioxide is a commonly referred example, in which the use of new input substances led to 16 times less waste generated[65]. It is evidently natural to consider principle 1 as relevant for chemicals policy. REACH at present, however, targets the substances, mixtures and articles that result from industrial processes, and not the industrial synthesis processes as such[66]. Similarly, principle 2 on *atom economy*, 6 on *energy efficiency*, 7 on *renewable feedstock* and 9 on *catalysis* are all strongly linked to chemical synthesis, but much less linked to the final industrial outcomes that at present fall under the scope of REACH. Consequently, for these five principles (1, 2, 6, 7 and 9), REACH is hardly relevant in its current state. No provision in REACH is found to give any clear guidance or direction for chemical synthesis as such, which creates a gap between the potential of green chemistry and current regulatory incentives, as far as industrial chemicals policy is concerned[67]. While REACH on the one hand focuses on market harmonisation (and thus on the outputs from chemicals industry, which circulate on the markets, rather than on the input substances), and on the other on health and the environment (and therefore also on the output, which people and other organisms are exposed to), this set up may seem natural. However, considering the broader dual objectives of REACH to promote both innovation and environment, this arrangement is not necessarily given. Companies generally gain from being stimulated to innovate and economise along the entire product chain, and from an environmental point of view,

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[63] See e.g. Chynoweth P (2008) Legal Research. In: Knight A and Ruddock L (eds.) *Advanced Research Methods in the Built Environment*. Oxford: Wiley-Blackwell.

[64] On environmental law methodology, see also McGrath C (2007) *Does environmental law work? How to evaluate the effectiveness of an environmental law system*. Saarbrücken: Lambert; and Nilsson A (2011) *Enforcing Environmental Responsibilities. A Comparative Study of Environmental Administrative Law*. Academic Thesis. Department of law. Uppsala: Uppsala University.

[65] Anastas and Eghbali (2010) op. cit.

[66] See also Lahl and Zeschmar-Lahl (2013) op. cit. on waste and risk cycles.

[67] However, see European Union policy and legislation on e.g. eco-design and regarding products at: https://ec.europa.eu/growth/industry/sustainability/ecodesign_en (accessed 18/11/2019).

the principles of green chemistry show that risks can be reduced from measures throughout life cycles of products. A well-designed regulatory development in line with these five green chemistry principles could therefore simultaneously promote both the innovation and environmental objectives of REACH[68].

Turning to the remaining principles that we evaluate, five of them (3, 4, 5, 8 and 10) are relevant for not only chemical synthesis as such, but also for emissions from industrial processes and for the environmental and health characteristics of REACH-regulated substances, mixtures and articles. They fall within the scope of REACH and are more or less promoted by various stipulations. The ambition in principle 3 to promote *less hazardous chemical syntheses*, i.e. to design methods to use and generate substances that possess little or no toxicity to human health and the environment, has clear relevance for both processes and products. While REACH with some exceptions is less relevant for the choice of substances used as inputs in a specific process, the regulation is significant for the substances and mixtures that are ultimately generated, for example, through the registration requirements in REACH and, potentially, through various other types of risk reducing provisions, including in the authorisation and restriction blocks. The latter is even more obvious for principle 4, *designing safer chemicals*, which means that chemical substances and mixtures should be produced in a way that minimises their eventual toxicity, and potentially also their persistency and potential to bioaccumulate. This principle is promoted by the CL and the authorisation and restriction requirements, despite regulatory inefficiencies and the fact that quite few substances are targeted so far. As an example, a group of substances managed here is the phthalates, which are used as e.g. plasticisers, of which several are classified as toxic to human reproduction. Some of these are restricted (e.g. DEHP, a reproductive toxicant) whereas others are placed on the authorisation (e.g. DIPP) or candidate (e.g. DCHP) lists. In these cases, promising substitutes are being developed, even though it remains to be seen how safe these are over time. It is also important to note, that for example DEHP was proposed to be restricted already under pre-REACH EU chemicals policy, in 2001, which illustrates how ineffective chemicals policy sometimes is[69]. Concerning principle 5, *safer solvents and auxiliaries*, avoidance of unnecessary auxiliary substances does not automatically follow from REACH, but REACH affects the ambition to use non-hazardous substances because products commonly contain more or less residues from production processes. Here, the authorisation requirement for the solvent formaldehyde provides one illustration[70]. In the case of principle 8, on *reducing derivatives*, REACH does not say much, but the regulation may be relevant in some cases. One example is derivates of benzotriazoles that may be used as UV stabilisers in e.g. textile fibres, of which at least one (2-(2H-benzotriazol-2-yl)-4,6-ditertpentylphenol) is on the CL[71]. Finally, REACH is of importance for principle 10 on *design for degradation*, foremost the various provisions promoting avoidance of persistent substances. The restric-

[68] Here, indicators for these principles, such as the referred E-factor, or the 'Atom efficiency' (which is the ratio of the molecular weight of the desired product over the molecular weights of all reactants used in the reaction), for principle 2, could be used to measure progress over time see e.g. Anastas and Eghbali (2010) op. cit.

[69] Swedish Chemicals Agency (2001) *Risk Reduction Strategy for DEHP*. Draft 2 July 2001. Stockholm: Swedish Chemicals Agency.

[70] See ECHA, at: https://echa.europa.eu/sv/substance-information/-/substanceinfo/100.105.544 (accessed 18/11/2019).

[71] See ECHA at: https://echa.europa.eu/information-on-chemicals/candidate-list-substances-in-articles-table (accessed 18/11/2019).

tion of decaBDE, a hazardous brominated flame retardant, is an example of this[72], even though, as in the case of DEHP, it took several years to reach that decision[73]. To summarise, these five principles (3, 4, 5, 8 and 10) are promoted by the regulation, but REACH could be more stringent and its implementation could be improved.

The remaining two principles, number 11 (on *analytical methods*) and 12 (on *accident prevention*) are of different type and have almost no link to the objectives of REACH.

While the evaluation above shows that certain requirements in REACH indeed promote some of the green chemistry principles, the regulation is far from explicitly designed for doing so, and the implementation is everything but optimal. We will now discuss how to potentially improve the situation.

Discussion

This article evaluates if and how REACH is a tool that promotes green chemistry. While we show that REACH, just as green chemistry, aims for both innovation and protection, the overall conclusion is that REACH is a weak driver of green chemistry. There are evident gaps between environmental goals and the green chemistry potential on the one hand, and regulatory requirements on the other.

Considering the four key building blocks in REACH, the provisions on registration require companies to generate data, which can be helpful for implementation of the green chemistry principles, since knowledge on substance properties is often missing. For high-quantity substances and SVHCs, REACH also stimulates data and information flows along supply chains, which helps producers, procurers and various other institutions to foster green chemistry. However, the registration block contains no explicit elements that relate to the green chemistry principles, and the data demands for most substances are either weak or non-existent. In particular the latter is problematic since also substances that sometimes are used in small quantities may have e.g. CMR properties, and therefore constitute risks. Moreover, the registration demands do not address potential effects of exposure to chemical cocktails[74], which are crucial to explore and describe in order to encourage green chemistry (e.g. principle 4). The REACH evaluation block also generates knowledge and data of value for green chemistry, but it includes comparatively few substances, which impede implementation of further risk reduction measures in the regulation.

Regarding the authorisation and restriction blocks, REACH is more relevant for green chemistry than when it comes to registration and evaluation, since the regulation explicitly identifies problematic substances and thereby signals them as more or less undesirable. It is for example reasonable for companies to expect that SVHCs on the CL sooner or later will be targets for additional control measures, such as authorisation requirements, even though these initially may be characterised by exemptions. Just as for evaluations, however, quite few substances have been targeted so far. The number of restrictions under REACH is also very low, given what science shows is needed in order to reach public environmental goals. Nevertheless, the regulatory set-up of REACH generally stimulates innovation away

72 See ECHA at: https://echa.europa.eu/sv/substance-information/-/substanceinfo/100.013.277 (accessed 18/11/2019).

73 See further about the decaBDE story in Eriksson J, Karlsson M and Reuter M (2010) Technocracy, politicization, and non-involvement: politics of expertise in the European regulation of chemicals. *Review of Policy Research* 27, 167–185.

74 Swedish Chemicals Agency (2015) op. cit.; Kortenkamp and Faust (2018) op. cit.

from substance properties included in the SVHC criteria.

All in all, REACH promotes certain green chemistry principles, in particular 3 (less hazardous chemical syntheses), 4 (designing safer chemicals) and 10 (design for degradation), even if the implementation so far is weak. There is moreover an untapped regulatory potential in REACH, in relation to several of the twelve principles. Even if REACH at present is not particularly relevant for waste prevention, atom economy, energy efficiency, renewable feedstock and catalysis, several of these five principles could be expressed in the regulation, because they relate closely to the regulations' dual objectives. For example, provisions are possible to formulate to steer towards renewable feedstocks, in line with the scope of REACH and in order to protect the environment and promote the economy, for example as a requirement to first hand seek to avoid fossil fuel-based polymers, as a kind of a substitution requirement.

There is thus room for improvements of REACH in order to promote green chemistry. To be more specific, not least the following measures and legislative amendments are conceivable as helpful for closing the goal-regulatory gaps identified:

- A general requirement on operators, to continuously strive towards producing and importing less hazardous substances, mixtures and articles. Expressing such a responsibility for continuous improvements is not uncommon in environmental law and would not be incompatible per se with a market oriented regulation.
- Fewer exemptions in REACH for specific categories of chemicals that are not regulated elsewhere with the same degree of protection as required by REACH, and a legal duty on operators to register also substances in lower quantities than 1 tonne per company and year. This stimulates knowledge and data generation.
- Inclusion of substances in articles in a more comprehensive manner in REACH, including for imported articles. This broadens the reach of the regulation to areas of relevance for ordinary consumers and public health, but also benefits forerunner companies that strive for phasing out for example SVHCs from articles.
- Increased data requirements for REACH registration, in relation to all quantities. This enables improved evaluation, as well as more rapid risk assessment processes and better outcomes, in turn incentivising green chemistry.
- Stringent demands on general and early substitution in REACH, and refusal of substance authorisation when less hazardous, well-known substitutes exist. Requirements are needed not only regarding authorisation, but also within the registration block, e.g. provisions on providing substitution plans early on. Due to the general lack of knowledge and data, it is important to develop a group-based approach, as a precautionary default in cases of uncertainty, in order to avoid regrettable substitution[75].
- Upgraded criteria for SVHC, for example, by including endocrine disrupting substances as SHVCs, and by broadening the coverage of P and B substances. It is also important to ensure that potential effects of mixtures of substances – e.g. when the toxicological effect of the mixture risks being greater than the sum of the

[75] To describe this, "[c]hemical substances can be grouped together in many different ways, such as by chemical structure, (eco)toxicological properties, function or areas of use [in order to] streamline work, and to prevent a substance with undesirable properties from being replaced with another substance of similar properties." From: Chemicals Agency (2018) *Grouping of chemical substances in the REACH and CLP regulations*. Report 2-18. Sundbyberg: Swedish Chemicals Agency.

effects of individual substances – are assessed and managed here.

- Increased transparency regarding data provided by industry and agencies, and enhanced responsibility to disseminate this information up and down supply chains. This facilitates for product designers to apply the green chemistry principles.

With amendments of REACH like these, which of course need to be developed in detail, the role of regulatory agencies becomes more active and many hazardous substances become less competitive. In parallel, it is important to reform the processes and the roles of the main committees under the REACH regulation, which at present operate in a too time and resource consuming manner.

The outcome of amendments like these likely strengthens the economic incentives for companies to invest in green chemistry research and green product design. Management measures taken by companies are namely helped by improved precision on what is to be considered as unacceptable risks and substances, and by improved access to information along supply chains. A well-designed policy and legal development along these lines thus incentivises substitution, stimulates research and innovation and enhances competitiveness among forerunners.

To conclude, substantial amendments of the REACH regulation are needed to set a legal structure that truly promotes green chemistry. Such changes are achievable if a revision process starts after the recently finalised REACH review, with a newly elected European Parliament and a new incoming European Commission. From a broader point of view, this fits well with EU's general intentions to be an international forerunner in the field of environmental policy in general and of chemicals policy in particular. Considering that the EU constitutes one of the largest markets in the world, and since REACH is internationally trend-setting, many companies likely benefit from such regulatory development, in addition to the gains from public and environmental health point of view that follow, all in all promoting a non-toxic environment.

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