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Economic assessment and valuations of environmental and health impacts caused by Perfluorooctanoic acid (PFOA) and its salts

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Economic assessments and valuations of environmental and health impacts caused by Perfluorooctanoic acid (PFOA) and its salts- Environment Working Paper No.128

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Foreword

This background paper on economic assessments and valuations of environmental and health impacts caused by PFOA and its salts was prepared for the SACAME workshop of 30-31 August 2017 in Ottawa, Canada, by Silke Gabbert of Wageningen University & Research, the Netherlands.

The workshop was organised in co-operation between the Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology (Joint Meeting) and Working Party on Integrating Environmental and Economic Policies (WPIEEP), and was hosted by Health Canada, with funding from the European Commission.

The paper was revised and takes into account feedback received from Delegates during and after the workshop and comments received from the Joint Meeting and WPIEEP by written procedure. The author would like to thank Nils Axel Braathen and Eeva Leinala of the OECD Secretariat for comments on previous versions of the paper. Work on this paper was conducted under the overall responsibility of Nathalie Girouard, Head of the Environmental Performance and Information Division. The indispensable support of Elvira Berrueta Imaz, Natasha Cline-Thomas and Stéphanie Simonin-Edwards in co-ordinating the editing and publication process is gratefully acknowledged.

The opinions expressed and the arguments employed are those of the author.

Table of contents

Foreword **3**

Acronyms and abbreviations **5**

Abstract **6**

Résumé **7**

1. Aims and scope of the report **8**

2. Role of economic assessments of PFOAs and its salts in different regulatory contexts **9**

3. Evaluation of existing assessments and valuation studies of PFOA and its salts **15**

4. A proposal for impact assessment and valuation of PFOA and its salts for socio-economic analysis **24**

5. Conclusions and implications for assessing social costs of PFOA and its salts in an SEA **35**

References **37**

Tables

Table 2.1. The concept of social cost in chemicals risk management 9
Table 3.1 Evaluation criteria used for the literature analysis 17
Table 3.2. Information on economic assessments and valuation analysis for PFOA and its salt 20
Table 3.3. Information on economic assessments and valuation analysis for PFOS[1] 23
Table 4.1. Key data requirements and possible data sources for a multimedia stock pollution assessment of PFOA and its salts 28
Table 4.2. Data for assessing stock dynamics of PFOA and its salts in an illustrative example 29
Table 4.3. Toxicological effects of human exposure to PFOA and its salts and corresponding impacts 33
Table 4.4. Technical reports suggesting and testing approaches for the assessment and valuation of health and environmental impacts for chemical risk management 34

Figures

Figure 2.1. Timeline of control actions and initiatives for PFOA and its salts at the national and the international level 14
Figure 3.1. Search terms for identifying scientific studies addressing socio-economic assessments or valuations of impacts 16
Figure 4.1. Components of the integrated multimedia stock pollution model 27
Figure 4.2. Illustrative example of assessing stock dynamics for PFOA and its salts in soil and water 31

Acronyms and abbreviations

APFO	Ammonium perfluorooctanoate
BPA	Bisphenol A
CBA	Cost-benefit analysis
CEA	Cost-effectiveness analysis
CIA	Climate impact assessment
CLP	Classification, Labelling and Packaging
CMR	Carcinogenic, mutagenic, toxic
ECETOC	European Centre for Ecotoxicology and Toxicology of Chemicals
ECHA	European Chemicals Agency
ED	Endocrine disrupting
EPA	Environmental Protection Agency
EU	European Union
GEA	General equilibrium analysis
HBCDD	Hexabromocyclododecane
OECD	Organisation for Economic and Co-operation and Development
PBDE	Polychlorinated biphenyls
PBT	Persistent, bioaccumulative and toxic
PFAS	Per- and polyfluoroalkyl substances
PFCA	Perfluoroalkyl carboxylic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PPCP	Pharmaceuticals and personal care products
RAC	Risk Assessment Committee
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RIA	Regulatory impact assessment
SCCP	Short-chain chlorinated paraffins
SEA	Socio-economic analysis
SEAC	Socio-Economic Assessment Committee
SVHC	Substances of Very High Concern
vPvB	Very persistent, very bioaccumulative

Abstract

Perfluorooctanoic acid (PFOA) is being used in fluoropolymer production, as surface treatment agents and for the manufacture of side-chain fluorinated polymers. However, there is evidence that PFOA and its salts have a number of hazardous properties that may cause harm to human health and the environment.

This report evaluates existing economic assessments and valuations of impacts arising from PFOA and its salts. The aims of this evaluation are to:

- identify the main health and environmental endpoints that were included in existing economic assessments;
- investigate the completeness of the assessments from a social cost perspective;
- analyse to what extent it was possible to value impacts arising from the identified endpoints;
- compare the social cost estimates provided; and to
- identify significant data or methodological gaps and to discuss options for assessing and valuing impacts of PFOA and its salts.

In total, 79 documents were surveyed. 10 of these documents address socio-economic issues of PFOA use and abatement by means of a quantitative assessment. All studies focus on assessing the abatement cost side of PFOA and its salts.

External costs arising from environmental and health impacts were not incorporated in the analyses. Hence, existing economic assessments do neither allow for conclusions about social costs of PFOA and its salts, nor for conclusions on social benefits from PFOA abatement.

The report also discusses conceptual requirements for a socio-economic analysis of PFOA and its salts, and options for improving assessments of impacts and social costs.

JEL codes: D61, D62, D83, I18, L51, Q51, Q52

Keywords: Cost-benefit analysis, regulatory impact assessment, environmental health valuation, non-market valuation, PFOA, PBT

Résumé

L'acide perfluorooctanoïque (PFOA) continue d'être employé comme adjuvant de polymérisation dans la production de polymères fluorés. Cependant, il est établi que le PFOA et ses sels présentent un certain nombre de propriétés potentiellement dangereuses pour la santé humaine et l'environnement.

L'objet du présent rapport est de faire le point sur les évaluations économiques et les évaluations d'impact du PFOA et de ses sels. Le but de l'exercice est le suivant :

- recenser les principaux effets pour la santé et l'environnement considérés dans les évaluations économiques existantes ;
- déterminer le caractère exhaustif des évaluations en ce qui concerne les coûts sociaux ;
- étudier dans quelle mesure il était possible d'évaluer les répercussions des effets mis en évidence ;
- comparer les estimations de coûts sociaux fournies ;
- mettre en évidence les lacunes importantes en matière de données ou d'ordre méthodologique susceptibles de compliquer l'évaluation des coûts sociaux et examiner les solutions envisageables pour évaluer les conséquences du PFOA et de ses sels et pour leur attribuer une valeur.

Au total, 79 documents ont été passés au crible. Dix des 79 documents étudiés traitent d'aspects socio-économiques de l'utilisation du PFOA et des restrictions le concernant dans le cadre d'une évaluation quantitative. Toutes les études s'intéressent aux coûts de la réduction de l'utilisation du PFOA et de ses sels.

Ces coûts sont calculés à partir d'évaluations marchandes. Les coûts externes induits par les répercussions pour l'environnement et la santé n'ont pas été pris en compte. Par conséquent, les évaluations économiques existantes ne permettent d'établir ni les coûts sociaux du PFOA et de ses sels, ni les avantages sociaux (coûts sociaux évités) de la réduction de l'utilisation du PFOA.

Codes JEL : D61, D62, D83, I18, L51, Q51, Q52

Mots-clés : analyse coûts-avantages, analyse d'impact de la réglementation, évaluation des risques sanitaires liés à l'environnement, évaluation non marchande, PFOA, PBT

1. Aims and scope of the report

The overall aim of the OECD project "Socio-economic Analysis of Chemicals by Allowing a better quantification and monetisation of Morbidity and Environmental impacts" (SACAME) is to support socio-economic analysis (SEA) of chemicals, which is an approach intended to offer support to regulatory decision-making of chemicals under REACH, but also under different national legislations. Based on the outcomes of a workshop held in June 2016 at the European Chemicals Agency (ECHA) it was decided to conduct five case studies of existing knowledge regarding economic valuations of health and environmental impacts caused by the use of specific (groups of) chemicals. These are (i) phtalates, (ii) mercury compounds, (iii) PFOA and its salts, (iv) 2-NMP, and (v) formaldehyde.

The focus of this report is on PFOA and its salts. In particular, the objectives of the report are

1. To review available economic analyses regarding PFOA and its salts. The review includes (i) studies on the risk management of PFOA and its salts conducted in OECD member countries and (ii) studies retrieved from the scientific literature;
2. To summarise the main endpoints that were addressed in these studies, and the uses targeted by risk management strategies;
3. To analyse to what extent it was possible to value impacts arising from the identified endpoints, to discuss the magnitude of social cost estimates provided in the studies considered; and to discuss whether additional valuations of these endpoint related impacts could have been attempted; and
4. To identify and evaluate any significant methodological and data gaps within and across the selected studies; and to discuss the completeness of the assessments from a social cost perspective.

The report is organised as follows: Section 2 discusses the role of (socio-) economic assessments of PFOA and its salts in different regulatory contexts. Using a criteria-based literature analysis, Section 3 presents a comparative evaluation of available economic assessments of PFOA and its salts. The evaluation considers the assumptions of the assessment, health and/or ecological endpoints addressed, and the methodological approach(es) and data used. Where possible, quantitative cost estimates retrieved in the assessment are presented. Furthermore, the completeness of existing economic assessments or valuations of impacts from using PFOA and its salts are discussed from a social cost perspective.

Conceptual requirements for a good economic assessment and valuation of PFOA and its salts are discussed in Section 5. In particular, due to their being persistent PFOA and its salts are stock pollutants. As a consequence, any form of SEA must be based on a proper assessment of stock pollution effects in different media. A multimedia stock pollution model that has been suggested earlier by Gabbert and Nendza (2014[1]) and (2015[2]) is introduced, and general implications of this approach for the assessment of the social costs of PFOA and its salts in an SEA are discussed. Furthermore, the paper discusses how information about the time path of pollution from persistent substances can be transformed into economic assessments of social costs. Section 5 discusses implications for improving assessments and valuations of impacts from PFOA and its salts for an SEA.

2. Role of economic assessments of PFOAs and its salts in different regulatory contexts

2.1. The concept of socio-economic assessment in chemicals' risk management and regulation

Besides their various benefits of use, chemicals can cause damages to human health and to the environment. The aim of risk management strategies and regulatory measures is, therefore, to ensure that these risks can be adequately controlled in the short- and long term. This requires balancing social benefits against social costs arising from impacts of chemicals use, and of strategies reducing or substituting use. Social costs are the sum of private (i.e. market-based) costs and the cost burden arising from net negative externalities (i.e. impacts from production and consumption that are not included in the price-quantity mechanism of a competitive market). Applying the concept of social costs to chemicals risk management, Table 2.1 shows examples of private and social costs from a use- and non-use perspective. Note that avoided external costs under a use-scenario become potential external benefits under a non-use scenario.

Table 2.1. The concept of social cost in chemicals risk management

	Private costs	External costs
Use scenario	Market-based costs related to the development, production, and retail of a substance. For example: -Research and development costs -Training costs of workers -Costs for manufacture -Marketing costs	Non-market costs arising from the production and use of a substance, for example: -Environmental damage costs from water, soil or air pollution caused by emissions during production and use of a substance -Health damage costs of workers -Health damage costs of consumers
Non-use scenario	Market-based costs related to an emission reduction or abatement of a substance. For example: -Research and development costs for substitutes -Installation costs of alternative (emission reducing) production technologies-Training costs for workers-Marketing and promotion costs of products including substitutes	Non-market costs of reduced emissions or the introduction of substitutes, for example: -Environmental or health damage costs of substitutes -Employment costs

To facilitate decision-making on the use or non-use of hazardous chemicals socio-economic analysis (SEA) has been incorporated in regulatory frameworks of different policy areas (e.g. fiscal management, business impact assessment, technology development) long before the new European chemicals legislation REACH entered into force. An overview of SEA applications in the regulatory decision-making of OECD

member countries is provided in OECD (2002[3]). However, the use of SEA, and the approaches applied, varied widely across countries.

Following a review of the OECD's Risk Management Programme in 1995, the OECD started in 1996 an initiative to develop tools and methods for guiding risk management decision-making. Specific attention was given to techniques, approaches and terminology of retrospective SEA, i.e. ex-post assessments aiming at improving future decision-making in the field of chemical risk management. The document "Guidance for conducting retrospective studies on socio-economic analysis" (OECD, 2000[4]) discusses different purposes of retrospective SEA, in particular (i) to investigate how an SEA is carried out, (ii) to assess whether the SEA had an impact on (regulatory) decision-making, and (iii) to analyse the appropriateness and technical adequacy of the assessment.

In 2000, the OECD published a report introducing a conceptual framework for SEA applications in the field of chemical risk management decision-making (OECD, 2000[5]). The report defined the aim of an SEA is "to assist in balancing the costs and benefits of potential risk management measures" (OECD, 2000, p. 33[5]).

Besides providing guidelines to socio-economic assessment based on the experiences, requirements and elements of SEAs conducted in OECD countries, the study briefly discusses tools for conducting an SEA, including qualitative approaches such as screening and ranking methods, and standard economic methods, for example cost-effectiveness analysis, cost-benefit analysis, and general equilibrium modelling.

A comprehensive Technical Guidance Document, offering a detailed discussion of the theoretical foundations of SEA in the context of chemicals risk management, and of the available tools and techniques for assessing different types of costs and benefits related to chemical use and regulatory strategies, was published in 2002. This study provided a more elaborate definition of SEA, stating that

> the aim of SEA within the field of chemical risk management is to assist the decision-making process by making explicit the implications of choosing one risk management option over another. By having information about the trade-offs associated with different options, decision-makers are able to make a more informed choice as to the best way forward (OECD, 2002, p. 30[3]).

The European chemicals legislation REACH (European Commission, 2006[6]), which entered into force in June 2007, explicitly incorporates SEA as a decision-support tool for adopting decisions on chemicals risk management. A key objective of REACH is to ensure that the risks caused by substances of very high concern (SVHC) are adequately controlled or that remaining risks are outweighed by socioeconomic benefits in cases involving substances without safe thresholds, like PBT, vPvB and certain CMRs and EDCs. SVHC are substances that meet the criteria for being classified as (i) carcinogenic, mutagenic or toxic for reproduction (CMR), (ii) persistent, bioaccumulative or toxic (PBT) or very persistent and very bioaccumulative (vPvB), (iii) endocrine disrupters (ED), or substances that (iv) give "rise to an equivalent level of concern" (European Commission, 2006[6]). SVHC shall under defined conditions be "progressively replaced by suitable alternative substances or technologies where these are economically and technically viable" (European Commission, 2006[6]). The two regulatory control mechanisms adopted in REACH are the authorisation and restriction process (European Commission, 2006[6]). Both regulatory instruments make use of SEA, which is generally defined as a tool to evaluate what costs and benefits an action will create for society by

comparing what will happen if this action is implemented as compared to the situation where the action is not implemented. Under the REACH authorisation procedure, an SEA is a compulsory part of an application for authorisation whenever the risks to human health or the environment from the use of an Annex XIV substance are not adequately controlled. Also when adequate control can be shown, an SEA may be produced by the applicant in support to his application. An SEA may also be produced by any third party in support to information on alternatives (ECHA, 2011[7]).

In the context of chemicals risk management and regulation, SEA has been used in different ways, and for different purposes. The conceptual setup of an SEA, therefore, can differ depending on the underlying aims. If, for instance, the assessment is conducted in order to facilitate the identification of most suitable (abatement) technologies of a company, an SEA usually focuses on private costs and benefits related to these technologies. If, to the contrary, the aim is to support or guide regulatory decision-making on the use, restricted use or non-use of chemicals, a social-welfare perspective, i.e. an assessment (and comparison) of the social costs and benefits of all actors in the economy, is required. Within REACH, an SEA aims to identify and assess all positive and negative impacts arising from the continued use of a SVHC, and to weigh them against the positive and negative impacts of policy scenarios in which where the chemical is removed from the market or replaced by an appropriate substitute. Hence, in REACH authorisation and restriction decisions an SEA adopts a social welfare perspective.

Notwithstanding, the purpose of an SEA differs between REACH authorisation and restriction procedures. Manufacturers, importers or downstream users who want to apply for an authorisation of a specific use of a substance must show by means of an SEA that socio-economic benefits of a continued use of the substance outweigh the risks (European Commission, 2006[6]), Article 60(4); (ECHA, 2011[7]), (Gabbert et al., 2014[8]). Thus, within REACH, an SEA is a forward-looking assessment. In a restriction dossier for SVHC, prepared by an EU Member State or ECHA, an SEA provides supportive information explaining why community-wide action is required and why the restriction proposal is appropriate. Furthermore, the SEA examines expected benefits and costs arising from the proposed restriction for different societal actors (manufacturers, importers, consumers, etc., (ECHA, 2008[9])). Therefore, in practice, submitting an SEA as part of a restriction proposal facilitates a proportionality assessment of a restriction proposal.

An SEA is conceptually and methodologically close to regulatory impact assessment (RIA), which is "a formalised, knowledge based and ex ante analysis of the positive and negative effects of proposed regulations" (Radaelli, 2009[10]).

2.2. Existing regulatory approaches to risk management of PFOA

Perfluorooctanoic acid (PFOA) and its salts belong to the substance group of per- and polyfluoroalkyl substances (PFASs). PFOA and its salts has a broad spectrum of uses in both industrial processes and in consumer products (OECD (2013[11]), ECHA (2015[12])). In particular, the synthetic industrial chemical PFOA is still being used as a polymerisation aid in fluoropolymer production (production of fluoroelastomers and fluoropolymers (Loveless et al., 2006[13])). Furthermore, PFOA-related compounds are used as surfactants and surface treatment agents (e.g. in silver halide photographic film, paints and fire-fighting foams) and for the manufacture of side-chain fluorinated polymers used in textiles, carpet and paper applications. Corresponding to the large

number of applications, PFOA-related compounds are used in various consumer products across many sectors (Stockholm Convention, 2017[14]).

Besides its useful properties there is ample evidence that PFOA and its salts have a number of hazardous properties that can harm humans and the environment. Specifically, PFOA and its salts have been included on the REACH Candidate List as SVHC due to PBT and CMR properties. Furthermore, there is evidence that PFOA may act as an endocrine disruptor at low doses (ECHA, 2015[12]). Corresponding to the risks that these properties may cause to humans and the environment, and responding to the growing use of PFOA and its salts worldwide, different risk management measures, addressing the production and use of PFOA and its salts, have been adopted during the past decade. In brief, they can be grouped into control actions at the national and the international level. A short summary of existing risk management measures is given below. For a detailed discussion of risk-reduction approaches for per- and polyfluorinated chemicals, including PFOA and other, specific long-chain PFASs, see OECD (2013[11]) and (2015[15]), Cousins et al. (2016[16]), and Vierke et al. (2012[17]).

2.2.1. Control actions at the national level

In 2006, Environment and Climate Change Canada and Health Canada negotiated an agreement with four companies from the perfluorinated products industry to voluntarily reduce the content levels of residual PFOA, residual long-chain PFCAs and residual precursors in perfluorinated products marketed in Canada (Environment and Climate Change Canada, 2017[18]). The aim was to achieve a reduction of product content by 95% by end of 2010, and to fully phase-out the use of PFOA by the end of 2015. Progress data provided by the participating companies showed that these targets were met by all companies in 2015.

Following two final screening assessment reports on PFOA and PFCAs conducted in 2012, the Canadian Government proposed to prohibit the manufacture, use, sale, import and export of PFOA and amended the Prohibition of Certain Toxic Substances Regulations to add PFOA in 2016.

Further regulatory control measures on the use of PFOA and its salts were introduced by the Norwegian and the German governmental authorities. In 2013, the Environmental Agency of Norway published an amendment to its consumer products regulation. As a result, PFOA has been prohibited in consumer products since June 2014. In addition, limit values restricting the use of PFOA in substances and mixtures, textiles, carpets, other coated consumer products, and for photographic coatings for film, paper or screen, were defined. Likewise, quality standards and reduction targets for PFOA and PFOS have been defined by several national governmental agencies in the EU and the United States., e.g. the German Environment Agency and the German Drinking Water Commission, the UK Drinking Water Inspectorate, and the New Jersey Department of Environmental Protection. A list of these guidelines is included in Cousins et al. (2016[16]).

2.2.2. Control actions and initiatives at the international level

In 2006, the US Environmental Protection Agency (US EPA) invited eight companies (Arkema, Asahi, BASF, Clariant, Daikin, 3M/Dyneon, DuPont and Solvay Solexis) leading in the production of per- and polyfluoroalkyl substances to participate in a voluntary Stewardship Program, aiming at reducing PFOA emissions by 95% by 2010 using the year 2000 as a baseline, and with the ultimate goal of eliminating PFOA, PFOA precursors and related chemicals from emissions and products by 2015 (US EPA

(2006[19]) and (2017[20])). The programme was successfully completed in 2015. In addition to the Stewardship Program, the US EPA requires companies since September 2013 to report their intent to manufacture (including import) PFOAs and its salts that are intended for use as part of carpets or carpet treatments, as well as intentions to import carpets already containing these chemical substances (US EPA, 2013[21]). Also, EPA proposed a new use rule under the Toxic Substances Control Act requiring manufacturers and importers to notify the EPA of any new use of PFOA and its salts in new products (US EPA, 2015[22]).

PFOA and APFO are restricted as substances or in a mixture for the supply to consumers according to regulation (EU) 317/2014 (European Commission, 2014[23]).

Under the European chemicals legislation REACH (European Commission, 2006[6]), PFOA and its salts have been considered to fulfil the criteria for being classified as persistent, bioaccumulative and toxic (PBT), and for being carcinogenic, mutagenic and toxic for reproduction (CMR) according to the CLP regulation (European Commission, 2008[24]). In July 2013, PFOA was identified as a Substance of Very High Concern (SVHC) under REACH (ECHA (2013[25]) and (2013[26])). As a consequence, PFOA and its salts were added to the "Candidate List", which includes those substances that can become included in Annex XIV of REACH, the so-called "Authorisation List". Due to the hazardous properties of PFOA and its salts, the existing evidence about human exposure, the technical difficulties and high costs associated with removing PFOA from contaminated sites, its wide-dispersive use, and its potential for environmental long-range transport, Norway and Germany decided to submit a restriction proposal for PFOA, its salts, and PFOA-related substances (ECHA, 2014[27]). Public consultations on the restriction report, and consultations on the draft opinion of ECHA's Socio Economic Assessment Committee (SEAC) were completed in 2015 and the proposal is currently being evaluated.

As explained in section 2.1, the aim of an SEA within the restriction decision process under REACH is to

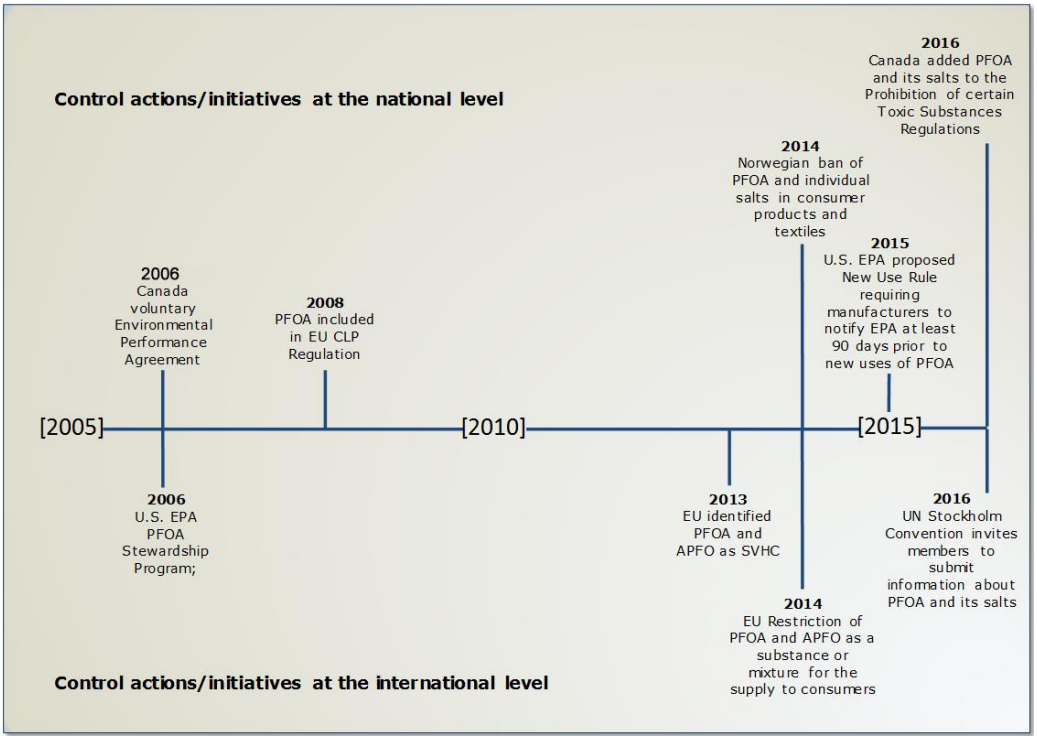
- justify the need for community-wide action
- assess whether the proposed restriction is most appropriate
- refine the proposed restriction
- provide an assessment of all positive and negative impacts of the proposed restriction as supportive information in the restriction proposal (ECHA, 2008[9]).

The SEA of the restriction proposal (ECHA, 2014[27]) offers an assessment of the expected human health, environmental, social, economic wider economic and distributional impacts arising from the proposed restriction (see also Section 3 for further details).

In September 2016, the 12th meeting of the Persistent Organic Pollutants Review Committee (POPRC.12) of the United Nations Stockholm Convention on Persistent Organic Pollutants adopted the risk profiles for PFOA, its salts and PFOA-related compounds. This initiated a review stage for this substance group, requiring a risk management evaluation that includes an analysis of possible control measures. Following on to this, member countries were invited to submit information about PFOA and its salts before 9 December 2016, resulting in a total of 71 submissions (see also Section 3 for further details).

A timeline of existing regulatory actions at the national and the international level is shown in Figure 2.1.

Figure 2.1. Timeline of control actions and initiatives for PFOA and its salts at the national and the international level



Source: OECD (2013[11]) and (2015[15]), Cousins et al. (2016[16]), Vierke (2012[17]).

3. Evaluation of existing assessments and valuation studies of PFOA and its salts

3.1. Selection of studies

Since REACH entered into force in 2007 there has been an ongoing debate among stakeholder groups (e.g. scientists, NGOs, decision-makers in regulatory authorities at the national and the European level) about the role and the scope of SEA in chemicals risk management decision-making (Bengyuzov (2016[28]), Hök (2016[29]), Annys (2016[30]), Rheinberger (2016[31]), Dubourg (2016[32])). Irrespective of the conceptual framing of an SEA, and of the specific regulatory decision-making context in which it is used, there has been general consensus that an SEA that feeds into regulatory risk management decisions of chemicals needs to adopt a social welfare perspective (ECHA (2008[9]), (2011[7]); Péry et al. (2013[33]), Gabbert et al. (2014[8]), Gabbert and Hilber (2016[34])).

Hence, an SEA should:

1. assess all positive and negative impacts of an on-going use of a substance, and of any possible policy strategy (e.g. an emission-reduction strategy, a phasing-out strategy, a ban)
2. balance positive with negative impacts in order to allow for conclusions if a proposed risk management action is adequate and efficient. Clearly, how impacts can be balanced depends on how they are valued.

To identify (socio-) economic assessments for PFOA and its salts, a systematic literature review was conducted. The review considered four main sources:

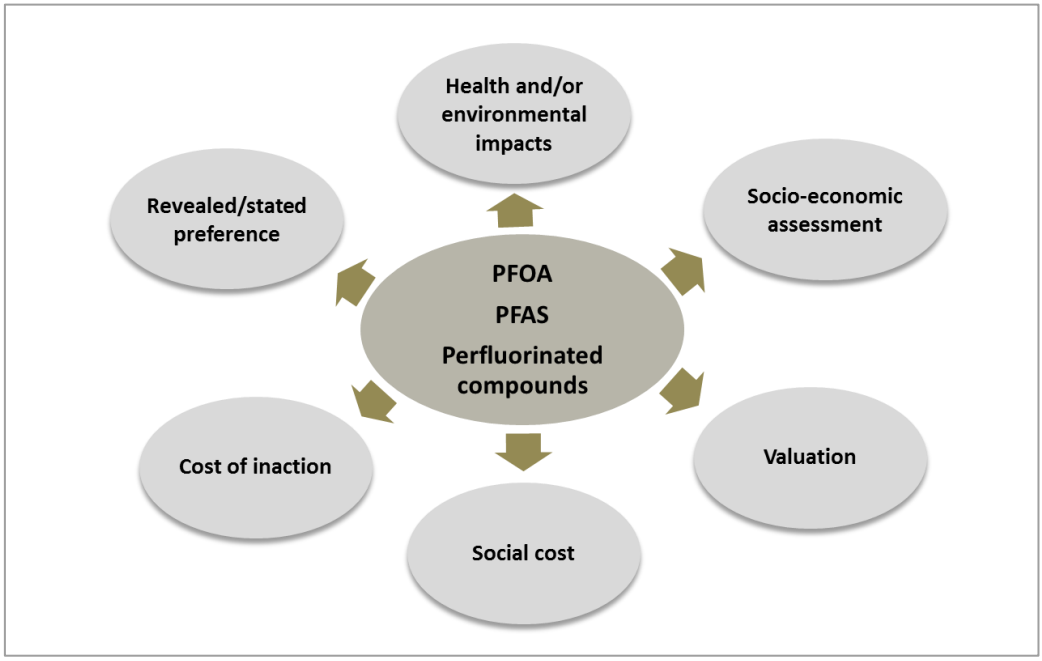
1. Information and (economic) assessments submitted to the UN Stockholm Convention on Persistent Organic Pollutants to support further evaluations of PFOA and its salts, cf. http://chm.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC12/POPRC12Followup/PFOAInfo/tabid/5453/Default.aspx;
2. The REACH Annex XV restriction proposal for PFOA and its salts (ECHA, 2014[27]), including the opinions provided by the ECHA Risk Assessment Committee (ECHA-RAC) and the Socio-Economic Assessment Committee (SEAC);
3. Economic assessments provided to support the prohibition of PFOA and its salts in Canada, cf. www.gazette.gc.ca/rp-pr/p2/2016/2016-10-05/html/sor-dors252-eng.php , and www.ec.gc.ca/toxiques-toxics/Default.asp?lang=En&n=6B9B6B28-1&xml=F68CBFF1-B480-4348-903D-24DFF9D623DC;
4. Economic analyses published in the scientific literature.

A keyword-based literature analysis was conducted in order to identify scientific publications addressing (socio-)economic assessments and existing economic valuations of health and environmental impacts arising from the use of PFOA and its salts. To ensure that the literature analysis captures a sufficiently broad spectrum of studies in the domain of socio-economic assessment and valuation, the search was based on combinations of substance group terms (e.g. PFOA, PFAS) with a term reflecting core

terminology in SEA (Figure 3.1). This revealed a total number of 18 combinations of search terms.

The search was conducted by means of two online literature databases, Scopus (www.scopus.com/search/form.uri?zone=TopNavBar&origin=recordpage) and Google Scholar. Keywords and search terms were identified from the title, the abstract, and the keywords of the study.

Figure 3.1. Search terms for identifying scientific studies addressing socio-economic assessments or valuations of impacts



3.2. Evaluation criteria

To allow for a systematic evaluation of the retrieved studies, a set of pre-defined criteria shown in Table 3.1 was used.

Table 3.1 Evaluation criteria used for the literature analysis

Criterion	Description
Regulatory or risk management context of the study	E.g. REACH, Stockholm Convention, national regulation
Methodological approach	E.g. cost-effectiveness analysis, cost benefit analysis, multi-criteria analysis, impact pathway approach
SEA included	Is a comprehensive or a partial SEA included in the assessment?
Assumptions underlying to the assessment	E.g. assumption regarding the spatial scale, emissions and release, specific parameter values used in the assessment
Time horizon of the assessment	E.g. short- or long-term assessment, time span of the assessment
Effects/endpoints/impacts considered	E.g. different types of environmental and health effects, endpoints, impacts
Valuation method	E.g. monetary or semi-monetary valuation, non-monetary valuation, no valuation applied
Aggregation mechanism for different types of impacts	Are different types of impacts aggregated into a social cost estimate and what method is used for this?
Data sources	How are the data for the assessment documented?
Documentation of data or knowledge gaps	Does the study point to data or knowledge gaps?
Treatment of uncertainties	Are uncertainties identified and documented, what kind of method is used (e.g. confidence intervals, statistical analyses, probabilistic assessment)

3.3. Results of the evaluation

This section summarises the results of the evaluation of existing assessments of PFOA and its salts.

The evaluation covered the information provided by governmental authorities according to Annex F of the Stockholm Convention, scientific studies and reports, data sheets, and policy documents.

Overall, 79 documents were included in the evaluation. Of these, 72 documents include information on PFOA, its salts and PFOA-related compounds submitted to the Stockholm Convention. Where possible, the supporting material was also considered, e.g. referred to in the forms submitted to the Stockholm Convention. The keyword-based literature analysis retrieved 5 documents. Furthermore, the REACH Annex XV restriction proposal for PFOA, its salts and PFOA-related substances (ECHA, 2015[12]), and the information provided in the context of the suggested amendment of the Canadian List of Toxic Substances Managed under Canadian Environmental Protection Act (1999), was included in the analysis. Complementary to these studies, though being beyond the scope of this report, a Canadian regulatory impact analysis statement on Perfluorooctance Sulfonate (PFOS) was included. In comparison to the available information about PFOA, the document contains a more comprehensive regulatory impact analysis, addressing expected social costs *and* benefits.

Only 10 of the 79 documents (~13%) included a socio-economic assessment, i.e. structured quantitative or at least semi-quantitative analyses of impacts, costs or benefits, or specific components thereof related to the risk management of PFOA and its salts.

Results from evaluating these studies are shown in Table 3.2 and Table 3.3. Of the remaining 69 documents, some included "socio-economic considerations". These are purely qualitative and, therefore, were not considered as "socio-economic assessment".

The *main findings* from the literature analysis can be summarised as follows:

- Economic assessments included in the evaluation refer to three regulatory contexts, i.e. the Canadian Regulations Amending the Prohibition of Certain Toxic Substances Regulations 2012, the Canadian Environmental Protection Act, 1999, and the restriction process under the European Chemicals' legislation European REACH (EC 2006[7]). Quantitative economic assessments related to other regulatory contexts, e.g. national regulations or the US EPA Stewardship Program, could not be identified.
- Of the 79 studies evaluated, only the regulatory impact analysis of PFOS conducted by Environment and Climate Change Canada (2006[35]) provided a comprehensive and in large parts monetary assessment of costs and benefits (Table 3.3). Although the evaluation of impact assessments for PFOS are, strictly speaking, beyond the scope of this report, the regulatory impact assessment conducted by Environment and Climate Change Canada (2006[35]) is the only case in which both costs and benefits incurred by different stakeholder groups were quantified and partially monetised. On the cost side, discounted costs of economic impacts accruing to industry and the Canadian government were assessed over a period of 25 years. The benefits side provided discounted monetary estimates of avoided costs for alternate water supply. However, due to limited data availability, several impacts (e.g. environmental impacts, health impacts, social impacts, wider economic impacts) were not included in the analysis.
- Most studies on PFOA impact assessment focus on environmental abatement costs. More specifically, they assess direct costs to industry, governments or both from a prohibition or a phase-out of PFOA, its salts, or per- and polyfluorinated substances. In addition, costs of switching to alternative substances or technologies are quantified. The cost assessments are obtained by means of a market-based valuation. External (i.e. non-market) costs, i.e. environmental and health costs arising from impacts of PFOA and its salts, are not assessed. Likewise, benefits of PFOA abatement are not addressed. The assessments of Bernier et al. (2014[36]), Wolf (2011[37]), Krishnan et al. (2003[38]) and UNEP (2012[39]) focus on private costs for emission reduction or emission abatement of PFOA and its salts and PFCs in general. Specifically, Bernier et al. (2014[36]) compare the effectiveness of conventional and alternative leachate technologies for reducing pharmaceuticals and personal care products (PPCPs), Bisphenol A (BPA), Polychlorinated biphenyls (PBDEs) and PFCs (including PFOA) at different Canadian sites. The effectiveness is expressed in terms of costs (annualised capital unit costs, operating costs) per cubic meter leachate and wastewater processed. The assessment shows that costs per cubic meter decrease with increasing treatment capacity. The study of Wolf (2011[37]) provides cost estimates for different emission reduction technologies for greenhouse gases, including PFCs. Hence, the estimates do not specifically refer to PFOA only.
- The SEA framework adopted in REACH (ECHA (2008[9]) and (2011[7])) requires an assessment of all positive and negative impacts arising from chemicals use or any regulatory control measure. These include economic impacts, environmental and health impacts, social and wider impacts on trade, competition and development (ECHA (2008[9]) and (2011[7])). Assuming that the risks of PBT or

vPvB substances can generally not be predicted (ECHA (2015[40]), p. 161), the Annex XV restriction proposal on PFOA and its salts focuses on a qualitative discussion of (avoided) impacts. As a result, the economic assessment presented in the REACH restriction proposal factually relies on substitution costs only, i.e. a quantitative assessment of economic impacts. Social impacts, wider economic impacts (e.g. impacts on employment) or distributional impacts were not considered or assumed to be very minor.

- Likewise, Oosterhuis and Brouwer (2015[41]) and Greßmann et al. (2014[42]) identified costs of different emission reduction or abatement measures, assuming that these costs reflect policy preferences for reducing the use of PFOA. Thus, it is assumed that abatement cost estimates can be used as a proxy for the avoided social damage costs from abatement. Since abatement costs capture environmental and health impacts from PFOA and its salts only indirectly, if at all, the cost assessments presented can, therefore, not be considered to adequately reflect social costs of PFOA abatement.
- The study of Malits et al. (2017[43]) provide an analysis of monetised direct and indirect costs resulting from low birth weight due to prenatal PFOA exposure. Direct costs include costs for hospitalisation for medical concerns associated to low birth weight. Indirect costs consist of a monetised estimate of a life-long loss in economic productivity due to a loss in IQ points, which is assumed to be caused by prenatal PFOA exposure. Furthermore, parental lost work days and out-of-the-pocket expenditures are included. Total economic costs for a period of 12 years (2003-2014) provide an aggregate estimate of the economic burden caused by prenatal PFOA exposure. It can also be interpreted as an estimate of the potential economic benefits if PFOA exposure will be reduced. The monetisation of the total IQ loss per year is achieved by means of value transfer, using monetary estimates of health care costs caused by childhood lead poisoning (Gould, 2009[44]).
- Overall, a comparison of quantitative cost estimates provided by different studies is hardly possible. The assessments differ strongly with regard to their focus, the time horizon of the assessment, and the datasets used. Whereas some studies presented assessments of capital and operating costs incurred by industry (e.g. caused by switching to new leachate technologies (Bernier et al., 2014[36]), using new solvent applications (Wolf, 2011[37]), regulatory impact assessments take a broader perspective by addressing costs accruing to different stakeholders (government, industry, consumers), which are – at least in the case of the regulatory impact assessment conducted for PFOS (Environment and Climate Change Canada, 2006[35]) – compared with a benefit estimate on the consumer side. However, both for PFOS and for PFOA, the methods underlying the assessment were not documented in the accessible documents. This constrains a methodological comparison of the assessments.

Table 3.2. Information on economic assessments and valuation analysis for PFOA and its salt

Type of economic assessment	Assessment or valuation method used	Effects, endpoints or impacts addressed	Values provided	Data or knowledge gaps considered
Malits et al. (2017[43]): Perfluorooctanoic acid and low birth weight: Estimates of US attributable burden and economic costs from 2003 to 2014				
Assessment of direct costs (costs of hospitalization for medical concerns), indirect costs (loss of IQ points) and other economics costs (out-of-pocket expenditures, parental lost work days) for low birth weight of children	Cost analysis (present value of total costs, discount rate 3%, assessment period 2003-2014) Monetisation of IQ loss is based on value-transfer	Present value of total (avoidable) costs from low birth weight due to prenatal exposure to PFOA.	Total (avoidable) costs (2003-2014): US $ 13.7 billion (US $ 9-40)	Uncertainty about the relationship between PFOA exposure and low birth weight; Uncertainty regarding the mechanisms underlying the PFOA exposure and low birth weight; Variation of values for direct and indirect cost components
Environment and Climate Change Canada (2016[45]) Regulations Amending the Prohibition of Certain Toxic Substances Regulations (2012)				
Estimates of governmental and industry costs arising from an amendment of the Canadian List of Toxic Substances to PFOA and its salts	Cost analysis (present value, discount rate 3%, assessment period: 10 years, 2014-2023)	Economic impacts of a prohibition of PFOA and its salts	No quantitative assessment of benefits available. Costs for industry were expected to be negligible (not quantified). **Total governmental costs** of the amendment CAD 383 000, including costs for compliance promotion (CAD 88 000) and costs for enforcement (CAD 295 000). Note that governmental costs refer to the amendment (applying to several substances) and not to individual substances.	Limited empirical studies; insufficient information on the range and distribution of existing data regarding production and uses of PFASs; uncertainties of emission projections; Knowledge gaps regarding production volumes, amounts used in products, trade, emission factors among life-cycle
Bernier et al. (2014[36]): Effectiveness of Conventional and Advanced in Situ Leachate Treatment				
Assessment of leachate treatment construction costs, capital and operating costs for different leachate technologies for PFCs (including PFOA) and design capacities (in USD_{2013})	Annualised cost based on market prices	Industry impacts	**Activated carbon filters**: USD 0.59 - 2.68 per cubic meter leachate and waste water processed per day **Reverse osmosis**: USD 5.77 - 7.09 per m³ processed **UV/H^2O^2 system**: USD 0.99 - 2.38 per m³ processed **UV/Fe^{2+}/H^2O^2 system**: USD 3.72 - 5.8 per m³ processed **UV/O_3 system**: USD 1.34 - 3.07 per m³ processed	Possible variation of cost estimates due to climate influence; variation in landfill waste; different regulatory standards applying to discharges into the environment, and variations in the treatment's technology level and capital costs, energy costs, operational costs
Wolf (2011[37]): Developing a California Inventory for Industrial Applications of Perfluorocarbons, Sulfur Hexafluoride, Hydrofluorocarbons, Nitrogen Trifluoride, Hydrofluoroethers and Ozone Depleting Substances				
Comparison of annualised capital and operating costs for different	Annualised cost assessment based on market prices	Impacts on industry	Cost estimates for perfluorocarbon emission reduction technologies	n.a.

emission reduction technologies from industrial applications of different greenhouse gases			**Film cleaning solvents**: USD 8 445 – 36 941 Vapour degreaser alternatives: USD 25 031 – 170 767 **Elimination of greenhouse gas solvents**: USD 25 031 – 56 685	
FluoroCouncil (2016[46]): Form for submission of information specified in Annex F of the Stockholm Convention pursuant to Article 8 of the Convention				
Estimates of R&D expenditures of Fluorocouncil companies for developing alternative polymerization aids and short-chain products and emission control technology; Estimates of transition and qualification costs of downstream users to replace PFOA and related substances	Monetised expenditures based on market prices	Impact on exposure; Impacts on industry	**R&D expenditures**: EUR 500 million Transition and qualification costs: EUR 1 million per use and company	n.a.
ECHA (2015[12]): Background Document to the Opinion on the Annex XV dossier proposing restrictions on Perfluorooctanoic acid (PFOA), PFOA salts and PFOA-related substances				
Calculation of deterministic cost effectiveness ratios for proportionality assessment of the proposed restriction, denoting substitution costs per kg of emissions or per kg of volume for a "post 2015" scenario; no assessment and valuation of impacts	Market prices for substitution of PFOA and related substances	Physicochemical properties; Long-range transport potential (atmospheric transport and marine transport); Persistence (P and vP); Bioaccumulation; Biomagnification; Potential to cause hypercholesterolemia; Potential to being carcinogenic (testicular cancer, kidney cancer, renal cancer); Developmental toxicity; Reduction of foetal growth in animals and in humans; Cost-effectiveness ratios refer to use volumes or	Cost-effectiveness ratio of PFOA substitution: **Production and imports:** EUR 0 per kg; **Fluoropolymer imports and use:** EUR 0 – 2 493 per kg based on volumes, EUR 0 – 6 561 per kg based on emissions; Textile use in EU: EUR 2 - 35 per kg based on volumes, EUR 100 - 1 750 per kg based on emissions; **Textile imports in articles:** EUR 2 - 35 per kg based on volumes, EUR 200 - 3 533 per kg based on emissions; **Fire-fighting foams:** EUR 4 - 53 per kg based on volumes, EUR 86 -1 143 per kg based on emissions; **Paper:** EUR 2 - 35 per kg based on volumes, EUR 10 - 1 750 per kg based on emissions; **Paints and inks:** EUR 2 - 35 per kg based on volumes, EUR 4 - 64 per kg based on emissions; **Photographic applications**:	Limited data on PFOA volumes in imported articles; Uncertainty regarding data on PFOA imports as substances and in mixtures and articles; Limited data on PFOA emissions into the environment from downstream user sites; Lack of knowledge to what extent PFOA has already been substituted in PTFE manufacture worldwide: Uncertainty regarding emission quantification; Uncertainty regarding DNEL and NOAEL values; Uncertainty regarding the serum concentration of PFOA in the dams; Extreme differences in half-lives between mice and humans; Uncertainty regarding import volumes of specific PFOA-related substances

		emissions; Impacts on industry	Expected to be very low (no estimate provided) **Total costs for PFOA:** EUR 0 - 6 561 per kg emissions **Total costs for PFOA-related substances:** EUR 4 - 3 533 per kg emissions	as a result of extrapolations; Limited information on cost differences between PFOA and PFOA-related substances
Greßmann et al. (2014[42]): Socio-Economic Analysis (SEA) in authorisation and restriction under REACH: Assessment of abatement costs of chemicals				
SEA framework based on cost-effectiveness analysis	Abatement costs of PFOS in EU as approximation of avoided social damage	Impacts on industry	**Reduction of PFOS for the whole range of imaging products**: EUR 20 - 40 million (replacement costs expected to be significantly higher) **Replacement of PFOS in hard metal plating**: EUR 2 million	Potential variation of abatement costs depending on the specific application of PFOS
Oosterhuis and Brouwer (2015[41]): Benchmark development for the proportionality assessment of PBT and vPvB substances				
Benchmark cost assessment for PBT/vPvB abatement measures embedded in a cost-effectiveness framework	Costs for abatement measures based on market prices	Impact on emissions Social impacts of abatement assuming that benchmark costs reflect policy preferences	**Substitution of fluoropolymers**: EUR 0 - 6 561 per kg of emissions avoided **PFOA substitution**: EUR 0 – 2 493 per kg substituted **Substitution of PFOA related substances**: EUR 2 - 53 per kg emissions avoided **Emission reduction of PFOA-related substances**: EUR 4 - 3 533 per kg emissions avoided	Uncertainty of cost estimates due to variation of emission estimates
Krishnan et al. (2003[38]): Alternatives to Reduce Perfluorinated Compounds Emissions from Semiconductor Dieelectric Etch Processes: Meeting Environmental Commitments while Minimizing Costs				
Comparison of substitution and abatement costs (including capital, switching and operating costs) for PFC	Environmental Value Systems Analysis for assessing incremental costs associated with different abatement and process options based on market prices	Impact on industry	USD 2.1-2.9 per wafer start	n.a.

Note: n.a.: not available.

Table 3.3. Information on economic assessments and valuation analysis for PFOS[1]

Type of economic assessment	Assessment or valuation method used	Effects, endpoints or impacts addressed	Values provided	Data or knowledge gaps considered
Environment and Climate Change Canada (2006): Perfluorooctane Sulfonate and Its Salts and Certain Other Compounds Regulation. Regulatory Impact Analysis Statement.				
Monetary assessment of discounted total industry and government costs over a 25-yesr period; Qualitative assessment of benefits for consumers	Cost-benefit analysis (net present value) of industry and government costs and consumer benefits over a 25-year period (5.5% discount rate).	Economic impacts and consumer benefits of a regulation of PFOS	**Costs incurred by industry:** Total discounted costs (net present value) of a disposal of PFOS (2008-2032): CAD_{2006} 230 671; Total discounted costs (net present value) of a replacement of PFOS (2008-2032): CAD_{2006} 496 830; Total discounted costs (net present value) for disposal and replacement of PFOS (2008-2032): CAD_{2006} 727 501; **Incremental costs per firm for upgrading to improved emission controls (depending on firm size):** - Capital costs of move to composite mesh pads: CAD_{2006} 46 499 - 176 033; - Operations and maintenance costs of move to composite mesh pads: CAD_{2006} 2 981 - 30 522; - Capital costs of current use of fume suppressant: CAD 0; - Operations and maintenance costs of current use of fume suppressant: CAD_{2006} 1 822 - 31 331 **Government costs:** - Present value of training of enforcement costs (25 year time frame): CAD_{2006} 570 450 - Present value compliance promotion costs: CAD_{2006} 176 203 **Consumer benefits:** - Avoided costs for alternate water supply: CAD_{2006} 560 000 per year **Net benefit of the regulation:** The total discounted cost to the private sector and federal government is estimated at CAD_{2006} 5.97 million, while total benefits to Canadian society is estimated to be a minimum of CAD_{2006} 6.35 million. Overall, the present value of the proposed Regulations was estimated to result in a net benefit to Canadian society of approximately CAD_{2006} 384 410 (discounted at 5.5% over a 25-year period).	Due to data limitations, not all benefits could be monetised and included in the analysis. The benefits to Canadians do not include non-quantified benefits such as value placed on ecosystem risk reduction associated with less PFOS use.

[1] Though PFOS is not included into PFOA and its salts, the document was included into the evaluation because it was the only available document offering a comprehensive and in large parts monetised assessment of social costs and benefits of the proposed regulation.

4. A proposal for impact assessment and valuation of PFOA and its salts for socio-economic analysis

As illustrated in Table 2.1, social costs comprise both market-based and external costs. The results of literature analysis presented in Section 3 underlines that existing economic assessments have predominantly focused on the assessment of market-based costs and benefits related to the reduction or substitution of PFOA and its salts and PFOS. External costs were generally not included in the assessments. Existing studies, therefore, do not allow for conclusions on social costs of risk management measures or regulatory actions for PFOA or PFOS. Furthermore, since the purpose of the assessment, the methodological setup, and the parameters considered differed across studies, quantitative cost estimates cannot be compared across studies.

The still incomplete picture about social costs, in particular of using PFOA and its salts, raises the question how impacts assessment can be carried out in a more comprehensive way in order to allow for evaluation (or at least approximating) social costs and benefits of PFOA use and abatement. Though a detailed analysis of social costs of PFOA and its salts is beyond the scope of this case study, this section discusses possible methodological options and outlines the key conceptual and methodological steps for such assessment. In addition, data requirements and implications for further research are discussed.

Depending on the aim of an SEA, and the analytic or regulatory context within which it is conducted, a broad portfolio of methodological approaches to SEA has become available – see OECD (2002[3]) for an overview. Irrespective of the precise regulatory context, an SEA is only meaningful if its outcomes support transparent and coherent decisions on the continued use, the non-use, or the restricted use of substances. Hence, an SEA should adequately reflect the (regulatory) concern(s) of the substance or substance group assessed.

PFOA and its ammonium salt APFO have been identified as SVHC because they meet the criteria for being classified as toxic for reproduction according to REACH Article 57c. In addition, PFOA and APFO meet the criteria for being persistent (P) and very persistent (vP) according to REACH Article 57c (ECHA (2013[25]) and (2013[26])). Thus, the use of PFOA and its salt APFO triggers multiple regulatory concerns, which is also reflected by the results obtained from the evaluation of documents discussed in Section 3. While the evaluation revealed a broad range of potential effects and hazards, the existing scientific evidence for concluding on PBT and CMR properties seems to be most stringent. Furthermore, several studies emphasise the long-range transport potential and the wide-dispersive use of PFOA and APFO, implying impacts at the global scale (ECHA (2014[27]) and (2015[12])).

The standard approach to impact assessment and impact valuation of chemicals has been impact-pathway analysis, where in a first step emission data are transformed into exposure information (see, for instance, Rabl and Holland (2008[47]), Sørensen et al. (2016[48])). In a second step, exposure information is used to develop dose-response relationships for specific effects in order to derive information about potential health

impacts from a chemicals' use. The third step, then, is to transform impact information into values for decision making, e.g. by attaching monetary values to expected health care costs, costs due to productivity loss and the loss of well-being. Substances that are, in addition to being toxic, also persistent or very persistent (so-called PBT substances) differ categorically from those of non-persistent substances (Gabbert and Weikard (2010[49]); Gabbert and Nendza (2014[1]) and (2015[2])). Specifically, the potential health and environmental impacts of PBT substances result from complex interactions of the properties persistence, bioaccumulation and toxicity. The interactions cannot be regarded as simple additive aggregates. This poses specific conceptual requirements for impact assessment and the valuation of impacts of PBT substances that go beyond standard impact pathway analysis:

- If a PBT substance is emitted to the environment, it will not remain in the medium into which it was initially released. Instead, the substance will be diffused and transported between environmental media (air, water, sediment, soil, biota). The time-path of the exposure concentrations in different media depends on multiple factors related to the properties of the chemical as well as the characteristics of the environmental media into which it escapes (Mackay and Paterson, (1991[50]); Scheringer et al. (2004[51]); Fenner et al. (2005[52]); Klasmeier et al. (2006[53])). An assessment of impacts that feeds into an SEA therefore ought to capture the environmental distribution patterns of PBT substances.
- Environmental, health and economic impacts caused by PBT chemicals depend on expected environmental exposure concentrations. Contrary to toxic, but non-persistent substances, PBT chemicals can remain in environmental media and biota long after emissions ceased (Gabbert and Nendza (2014[1]) and (2015[2])). Thus, PBT substances, including PFOA and its salts, are stock pollutants. An impact assessment ought, therefore, to assess the time path of pollution arising from PBT use in order to capture stock externalities of PBT substances as impacts arise from the stock, not from the flow. The conceptual foundations of modelling stock pollution effects and its implications for decision-making on an optimal control of contaminants go back to Smith (1972[54]), Plourde (1972[55]), Keeler et al. (1972[56]) and Forster (1975[57]).
- A key result of these early papers is that defining optimal control strategies for stock pollutants requires adopting an explicit inter-temporal perspective. Furthermore, the optimal pollution level is usually non-zero if the use of products including contaminants creates a positive benefit. The implications of stock pollution effects of, for instance, greenhouse gas emissions or water contaminants have been discussed by, among others, Falk and Mendelsohn (1993[58]), Fleming et al. (1995[59]), and Hart and Brady (2002[60]). The latter study extended the early Computational General Equilibrium (CGE) modelling approaches to a dynamic optimal control model that allows determining the optimal dynamic strategy for controlling cumulative pollution.
- In the 1990s the stock pollution concept became widely used for developing economic models of controlling greenhouse gas emissions (Nordhaus (1992[61]) (1993[62]) and (1993[63]), Ulph and Ulph (1994[64]), Kolstad (1996[65]), Newell and Pizer (2003[66])). A simple two-period model of regulating persistent chemicals was proposed in Gabbert and Weikard (2010[49]). Gabbert and Hilber (2016[34]) developed a cost-benefit analysis model capturing stock externalities for optimal control of PBT substances.

- Due to their persistence the assessment and valuation of impacts from the use of PBT substances must assess both "early" impacts and costs (i.e. impacts and costs arising within the period of use) and "late" impacts and costs (i.e. impacts and costs that occur after emissions are reduced or stopped). A specific concern of PBT substances is that – depending on their degradation in different media – late costs can spread over longer time periods than costs that occurred during the emission period.
- Finally, a valuation of impacts should be flexible, i.e. allow for both monetary and non-monetary valuations. This is particularly relevant in cases where a PBT substance is characterised by a broad use profile, which may cause diverse environmental and health effects and impacts, and where a meaningful monetisation is not possible due to incomplete, highly uncertain or lacking data.

The following subsections discuss these conceptual requirements in more detail with specific reference to PFOA and its salts.

4.1. Assessing environmental distribution patterns of PFOA and its salts

For a given emission path the environmental distribution of a substance can be determined using multimedia fate modelling based on the "fugacity" concept according to Mackay (2001[67]). Accounting for the exchange processes between environmental media, transformation or degradation processes, and advection processes that move the chemical out of the modelled system multimedia fate models provide forecasts of expected environmental concentrations. More specifically, results of multimedia fate models inform about where a substance will be in the environment, how much of it will be there and for how long. Throughout the past years different types of models have become available, which are characterised by different levels of complexity (Webster et al., 2005[68]). A main outcome of multimedia fate models are fraction releases of emissions into different environmental media (e.g. water, sediment, soil, biota) at steady state.

4.2. Assessing the time path of pollution

Due to their persistence, PBT and vPvB substances are stock pollutants. The relationship between the pollution stock P_t, emissions x and the decay rate δ of the chemical can be illustrated by the following general differential equation (Gabbert and Nendza (2014[1]) and (2015[2]), EC 2017):

$$\dot{P}_t = x - \delta P \qquad (1)$$

$\dot{P}$ denotes the change of the stock as a marginal unit of time elapses. The decay rate δ is obtained from data on the degradation half-live of a PBT/vPvB substance in specific medium. According to eq. (1) the change of pollution stock at any time t depends on emissions, which are assumed to be constant, minus the fraction of the stock that decays. Solving the differential equation (see Gabbert and Hilber (2016[34]) for details) gives

$$P_t = P_0 e^{-\delta t} + \frac{x}{\delta}\left(1 - e^{-\delta t}\right) = \left(P_0 - \frac{x}{\delta}\right) e^{-\delta t} + \frac{x}{\delta}. \qquad (2)$$

Following (2), at any time t the pollution stock P_t depends on the initial stock P_0 (i.e. the environmental stock at the beginning of an assessment period), the additional inflow of pollutants x and the decay rate δ. The latter parameter depends on and reflects the

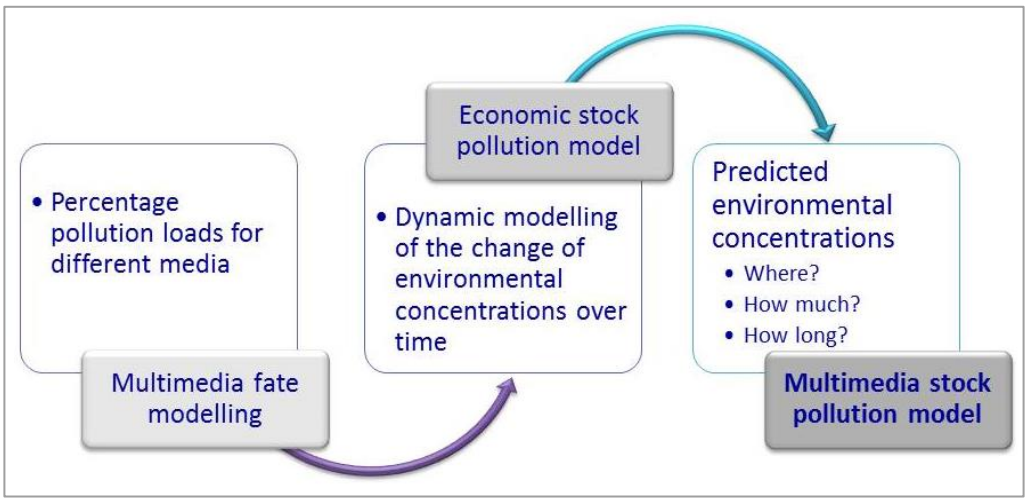
conditions of the compartment. The pollution stock P_t can be expressed as absolute stock (mass) or a concentration (mass per weight unit).

Gabbert and Nendza (2014[1]) and (2015[2]) propose an approach that combines multimedia fate modelling (Section 4.1) with economic stock pollution assessment into an integrated multimedia stock pollution model. In a nutshell, using the fraction releases into water, air, soil and sediment (including suspended sediment and biota) obtained from multimedia fate modelling as factors to determine the fraction or amount of emissions that is released per period into water, soil, air and sediment allows determining for any emission scenario

1. the time path of pollution in different media
2. the medium or media where the expected stock resulting from PBT or vPvB emissions will be highest
3. the time path required for a PBT or vPvB substance to degrade after reducing or eliminating emissions.

The approach has been suggested by Gabbert et al. (2018[69]) in a project financed by the European Commission[1] to determine long-term pollution paths in the environment and expected impacts of selected PBT and vPvB substances, including PFOA and its salts. Figure 4.1 illustrates key components of the approach.

Figure 4.1. Components of the integrated multimedia stock pollution model



Source: Adapted from Gabbert et al. (2016[70]).

[1] Approach for Evaluation to PBTs Subject to Authorisation and Restriction Procedures in the Context of Socio-Economic Analysis, contract no. 30-CE-0830972/00-26.

Table 4.1. Key data requirements and possible data sources for a multimedia stock pollution assessment of PFOA and its salts

Information/data requirement	Options	Source
Spatial area of emissions	Local, regional, continental, global	EUSES (2008[71]), EPISuite™ (US EPA, 2008[72])
Volume and mass values for different environmental media		EUSES (2008[71]), EPISuite™ (US EPA, 2008[72])
Emission data	Local, regional, continental, global emissions	Global emission data: Emissions within EU:
Compartment-specific degradation half-lives		EU risk assessment reports, ECHA Annex XV proposals, ECHA Annex XV restriction proposals
Emission period	Includes both data on emission history and emissions during the SEA assessment period	Depends on the assumed scenario and data availability
Fraction releases into different environmental compartments		Multimedia fate models (different levels of complexity)

The implications of the approach for impact assessment and impact valuation of PFOA and its salts can be illustrated with a stylised example of assessing stock dynamics of PFOA in soil and water based on the data and assumptions summarised in Table 4.2 Following emission information provided in ECHA (2015[12]), an emission period of t = 76 years is assumed, ranging from 1951 to 2027. This range covers the period for which emission data were documented in the literature. Within this period it is assumed that an SEA for PFOA and its salts is conducted for the time from 2016-2027. This period is called the SEA assessment period.

Table 4.2. Data for assessing stock dynamics of PFOA and its salts in an illustrative example

Model parameter		Source
Spatial area of emissions	Continental	Environmental volume and mass data retrieved from EUSES (2008[71]) and EPISuite™ (US EPA, 2008[72])
Emission period t [years]	77 (1951-2027)	Own assumption based on information provided in ECHA (2015[12])
Assumed SEA assessment period [years]	12 (2016-2027)	Own assumption
Emissions x [tonnes]	Mean cumulative global emissions 1951-2003: 4 064.5 Mean cumulative global emissions 2004-2015: 2 440 Mean cumulative global emissions 2016-2027: 2 310	ECHA (2015[12])
Emission scenarios	Scenario (i): On-going emissions Scenario (ii): Emission stop after 6 years of SEA emission period	Own assumptions
Compartment-specific degradation half-lives [days]	$t_{1/2}$ water: No significant degradation within 110-259 days $t_{1/2}$ soil: No significant degradation after 259 days $t_{1/2}$ sediment: No significant degradation after 259 days $t_{1/2}$ air: 130 days	ECHA (2013[25]) and (2013[26]), Vierke et al. (2012[17])
Degradation scenarios	Degradation half-lives for water, soil and sediment equivalent to REACH P-threshold	ECHA (2017[73])
Fraction release if emissions into soil and water[%]	Water: 14 Soil: 80	Own assumptions
Residence time water [days]	40	EUSES (2008[71])
Residence time air [days]	0.7	EUSES (2008[71])

Two emission scenarios are compared. In scenario (i) on-going, constant emissions over the entire SEA assessment period were assumed. Emission scenario (ii), to the contrary, assumes an emission stop after 6 years of the SEA assessment period. Furthermore, fraction releases are assumed to be 80% for soil and 14% for water. For PFOA and its salts no significant degradation could be determined within specific time-frames in water, soil and sediment (ECHA (2013[25]) and (2013[26])). Hence, the degradation half-lives for soil are above the REACH vPvB criteria for water, sediment and soil, but their precise values are unknown.

Figure 4.2 shows the plots of stock dynamics for soil and water. The solid lines denote stock dynamics for emission scenario (i), and the dashed lines for emission scenario (ii). Though the example is based on a number of simplifying assumptions, it warrants some general conclusions about the environmental pollution properties of PFOA and its salts:

- Due to being very persistent, on-going emissions cause the environmental exposure concentrations to increase over time.
- The change of the stock over time in environmental compartments depends on multiple parameters. For given emissions and the assumed release fraction, the medium-specific degradation half-live and the residence times in water and air are crucial. Although PFOA and its salts do not significantly degrade in water, soil and sediment, stock dynamics for PFOA differ considerably between these media. Besides the different fraction releases, which influence the amount of the substance that is emitted into a medium per period, the short residence time in water causes the stock to decline quickly if emissions are reduced. This underlines

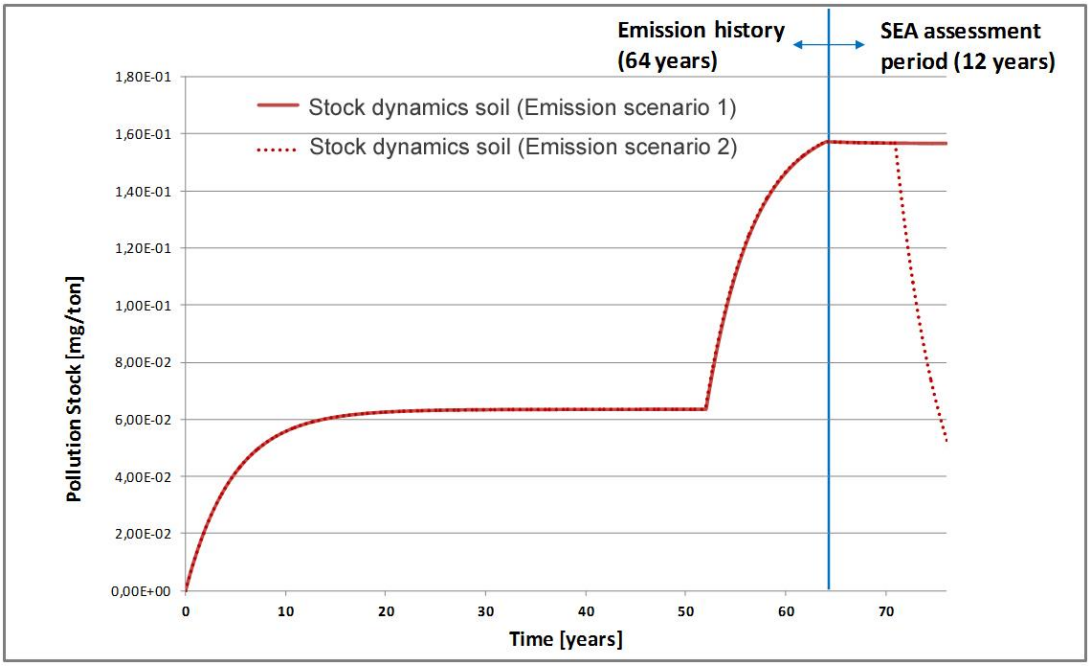
that it is crucial for impact assessments to reflect the accumulation patterns of PFOA and its salts in different media and over the entire emission and degradation period.

- PFOA and its salts have been used for several decades. Due to its long emission history the stock at the beginning of an SEA assessment period (in the example: after 64 years, i.e. in 2016) is non-zero. Consequently, environmental and health impacts of an applied-for-use and a policy scenario (e.g. an emission stop) must start with investigating the initial stock and corresponding (expected) impacts at the starting period of the assessment (i.e. 2016 in the illustrative example).
- An SEA usually compares (valued) impacts of an applied for use scenario (e.g. on-going emissions) with a specific policy scenario (e.g. an emission stop). Due to stock pollution properties, it can take decades or even longer for a substance to completely degrade or disappear. A crucial requirement for an assessment of social costs arising from PFOA and its salts is, therefore, to assess for each scenario impacts that are expected to occur during the emission period (so-called "early impacts") *and* the remaining impacts after emissions were reduced or stopped (so-called "late impacts"). Hence, social costs under emission scenario 1 are the present value of impacts arising from the stock given by the area under the solid curves in Figure 4.2. For emission scenario 2, to the contrary, social costs are the present value of impacts arising from the stock under the solid curves until year 71 (emissions stop), and of impacts from the stock given by the areas under the dotted line (after the emission stop). Note that an assessment of social costs that includes late impacts, should cover the entire time span of PFOA and its salts until it is fully eliminated or degraded to negligible environmental concentrations.

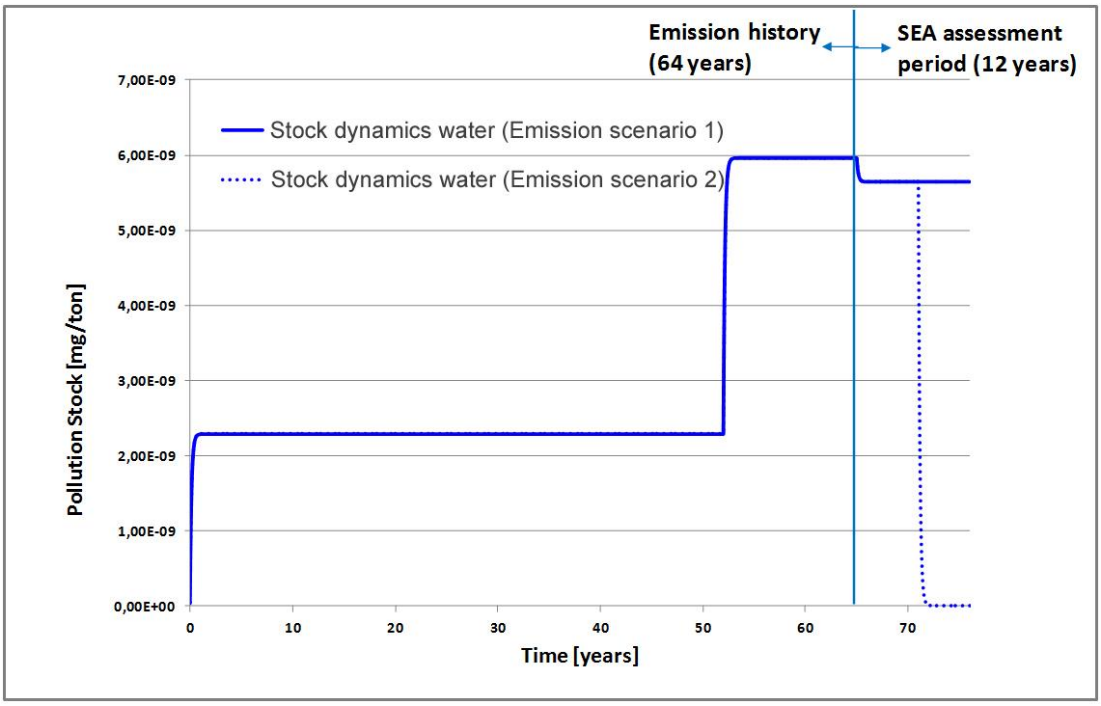
Figure 4.2. Illustrative example of assessing stock dynamics for PFOA and its salts in soil and water

Solid line: on-going emissions. *Dashed line:* emissions stopped after 6 years of the SEA assessment period

Panel a: Soil.



Panel b: Water



Source: Own calculations based on data and assumptions shown in Table 4.2.

The multimedia stock pollution model is data-driven and based on a number of assumptions. In particular, the choice of the spatial scale and environmental release fractions are crucial for the assessment. And several parameters feeding into the assessment can be highly uncertain. Hence the time path of pollution in different compartments does not necessarily reflect the "true" environmental exposure concentrations. Still, it offers a coherent and feasible way to assess the environmental pollution patterns of persistent substances. Furthermore, it captures the temporal and spatial dimension of environmental exposure, which is the basis for an assessment of social costs. Also, it allows for a forward-looking assessment of the expected time path of pollution in different media.

This approach goes beyond dynamic substance-flow analysis suggested by Li et al. (2016[74]), which focus on emissions only, and which ignores the ability of PBT or vPvB substances to remain and accumulate in the environment for long periods of time. Similarly, Zhu et al. (2016[75]) have suggested an approach for SEA applied to HBCDD under the Stockholm Convention. They offer a monetary assessment of the "gross economic costs" from reducing HBCDD use under different scenarios, covering the economic loss of the manufacturing sector, substitution costs of the use sector, and supervision costs of the government. Furthermore, the authors provided non-monetary estimates of social impacts and environmental benefits. The assessment of gross economic costs and environmental benefits relies on nominal emissions only, which is insufficient for an assessment of social costs as it ignores long-term impact due to stock pollution properties of the substance.

4.3. Impact assessment and impact valuation

So far, a commonly agreed definition of "impact" does not exist (Gabbert et al., 2014[8]). Generally, impacts denote the positive or negative consequences that are expected to occur in environmental media, biota and humans as a result of emissions and exposure. Such impacts are not equivalent to (toxicological and eco-toxicological) effects. Impact assessment, to the contrary, requires transforming effects data into information about (expected) positive or negative consequences. To gain insight into if, and how, an increase or decrease in pollution may affect impacts and, hence, environmental and health damage costs, it is necessary to explore the relationship between (change in) environmental concentrations, corresponding effects and (change in) impacts. Assuming that risk management decisions on the use or non-use of PFOA and its salts should apply a social cost perspective, there is a need for further research on how impacts of PBT and vPvB substances in general, and of specific compounds such as PFOA and its salts, can be derived.

Being a stock pollutant, multimedia stock pollution modelling can inform about the long-term environmental pollution burden of PFOA and its salts (the "time path of pollution"). The illustrative example presented above implies that expected stocks are highest in soil,[2] though increasing environmental exposure is likely to occur in all environmental media. There is evidence that PFOA and its salts bioaccumulate in aquatic and terrestrial species. For PBT and vPvB substances, Gabbert et al. (2017[76]) suggested two possible options for impact assessment:

[2] This conclusion is subject to the data used and the assumptions made as summarised in Table 4.2.

1. Comparative impact assessment based on, for example, single-species extrapolation, environmental limit, tolerance or acceptance values. This allows determining when environmental or health impacts can be expected to occur.
2. Probabilistic or semi-probabilistic modelling of impacts, e.g. using the concept of species sensitivity distributions (SSD, see, for example, OECD (1992[77]), Wenzel et al. (2015[78]) and Belanger et al. (2017[79])). Depending on available data (see, for example, Camboni et al. (2016[80])), the goal is to gain insight how expected impacts change due to changes in environmental exposure.

Furthermore, because the substance is considered to biomagnify along the food chain (ECHA, 2014[27]). Hence, without effective regulatory measures, increasing stocks in the environment may lead to increasing impacts in humans. Human exposure is considered to occur mainly through inhalation (air and dust), drinking water consumption, and ingestion (food). An overview of toxicological endpoints in humans, and corresponding impacts arising from human exposure to PFOA and its salts, are summarised in Table 4.3.

Table 4.3. Toxicological effects of human exposure to PFOA and its salts and corresponding impacts

Effect	Impact
Repeated dose toxicity	Liver damage Lipid metabolism (increase of cholesterol levels)
Carcinogenicity	Liver and kidney tumour development
Developmental toxicity	Decreased foetal growth in human and non-human mammalian species, IQ loss
Endocrine disrupting effects	Damage of the endocrine system, e.g. change of thyroid hormones

Source: ECHA (2014[27]).

Research on the environmental and health impacts of PFOA and its salts that captures the time path of pollution is still in its infancy. One reason is that the data necessary for such assessment are incomplete or lacking (ECHA, 2016[81]). However, though the assessment of environmental and health impacts arising from persistent chemicals such as PFOA and its salts is non-trivial, its complexity can be considered conceptually similar to the analysis of risk management of pollutants in other domains, e.g. transboundary air pollution, climate change, or waste management. Corresponding to model development in these domains, the key challenge is, then, to invest into the development of integrated assessment frameworks combining toxicological and eco-toxicological with socio-economic modelling. For enabling an assessment of social costs of a particular use scenario, such frameworks need to link information about the time path of pollution in the environment with dose-response and exposure-impact information for a broad set of environmental, health, and economic impacts.

In order to account for different policy preferences, the valuation of impacts should allow for both a monetary and a non-monetary valuation. Several studies have suggested approaches for assessing health impacts and for transforming impact information into monetary values (Table 4.4). Though the approaches have not been applied to PFOA and its salts, the direct and indirect cost estimates associated with, for example, mortality and morbidity cost values resulting from different types of cancer, or costs due to productivity loss as a result of a lower IQ, can be assumed to be generic and may justify value transfer of health impacts to PFOA. For instance, Malits et al. (2017[43]) used health costs from childhood lead poisoning for determining the costs of IQ loss caused by a prenatal exposure to PFOA. If impacts cannot be monetised, an aggregation of different types of

impacts is not straightforward. Here, multi-attribute decision analysis (see, for example, Xu (2015[82])) provides a set of methods for coherently aggregating impacts expressed in different units while accounting for the uncertainty inherent to all data.

Table 4.4. Technical reports suggesting and testing approaches for the assessment and valuation of health and environmental impacts for chemical risk management

Author(s)	Title	Year	Source
Alberini, A.	Measuring the economic value of the effects of chemicals on ecological systems and human health	2017	OECD Environment Working Papers No. 116, (Alberini, 2017[83])
Chiu, W.A.	Chemical risk assessment and translation to socioeconomic assessments	2017	OECD Environment Working Paper No. 117 (Chiu, 2017[84])
Navrud, S.	Possibilities and challenges in transfer and generalisation of monetary estimates for environmental and health benefits of regulating chemicals	2017	OECD Environment Working Paper No. 119 (Navrud, 2017[85])
ECHA	Valuing selected health impacts of chemicals. Summary of the Results and a Critical Review of the ECHA study	2016	(ECHA, 2016[86])
Camboni, M. et al.	Study on the Calculation of the Benefits of Chemicals Legislation on Human Health and the Environment Development of a System of Indicators	2016	(Camboni et al., 2016[80])
Sørensen et al.	Valuation literature on chemicals: A Description of an Inventory of Valuation Literature on Chemicals	2016	(Sørensen et al., 2016[48])
Rijk et al.	Health costs that may be associated with Endocrine Disrupting Chemicals. An inventory, evaluation and way forward to assess the potential socio-economic impact of EDC-associated health effects in the EU	2016	IRAS report 11 (2016), University Utrecht (Rijk, van Duursen and van den Berg, 2016[87])
ECETOC	Chemical Risk Assessment – Ecosystem Services	2015	Technical Report No. 125, (ECETOC, 2015[88])
Jongeneel et al.	Health Impact Assessment in REACH restriction dossiers	2014	RIVM Report No. 2014-0032, (Jongeneel et al., 2014[89])
Olsson, I.-M.	The cost of inaction: A socioeconomic analysis of costs linked to effects of endocrine disrupting substances on male reproductive health	2014	TemaNord 2014:557, (Olsson, 2014[90])
Verhoeven, J.K. et al.	From risk assessment to environmental impact assessment of chemical substances Methodology development to be used in socio-economic analysis for REACH	2012	RIVM Report 601353002/2012 (Verhoeven et al., 2012[91])
Bogaert, S.	Valuation of the results of the Environmental Impact Assessment project 2012 – RIVM Final report	2012	Report No. BE01120005670120 (Bogaert, 2012[92])
ECETOC	Environmental Impact Assessment for Socio-Economic Analysis of Chemicals: Principles and Practice	2011	Technical Report No. 113, (ECETOC, 2011[93])
Postle, M. et al.	Assessment of the Health and Environmental Benefits of REACH -- Part A: Methodology	2011	(RPA et al., 2012[94])
Postle, M. et al.	Assessing the Health and Environmental Impacts in the Context of Socio-Economic Analysis under REACH Final Report – March 2011 Part 1: Literature Review and Workshop Discussions	2009	(RPA et al., 2011[95])
Schuur, A.G. et al.	Health impact assessment of policy measures for chemicals in non-food consumer products	2008	RIVM Report 320015001/2008, (Schuur et al., 2008[96])
ECETOC	Counting the Costs and Benefits of Chemical Controls: Role of Environmental Risk Assessment in Socio-Economic Analysis	2008	Workshop Report No. 13 (2011), (ECETOC, 2008[97])
Rabl, A. and Holland, M.	Environmental Assessment Framework for Policy Applications: Life Cycle Assessment, External Costs and Multi-criteria Analysis	2008	(Rabl and Holland, 2008[47])
Pedersen, F. et al.	The impact of REACH on the environment and human health	2005	(Pedersen et al., 2005[98])

5. Conclusions and implications for assessing social costs of PFOA and its salts in an SEA

This report evaluates existing economic assessments and valuations of impacts attributed to PFOA and its salts. Surveying 79 documents, it was found that currently only few quantitative assessments of impacts and costs exist. Of these, most focus on economic costs, in particular direct costs arising to industry or governments from reducing emissions and from implementing PFOA-free technologies. Only one study, which did not address PFOA but PFOS, offered a cost benefit analysis, comparing economic costs of reducing PFOS emissions to consumer benefits. Assessments of health and environmental impacts, which determine the external, non-market based costs of PFOA and its salts, have not become available so far. Furthermore, impact assessments, which transform dose-response data of specific effects into (probabilistic) estimates of impacts, have not been conducted. As a consequence, economic cost estimates of regulatory measures cannot be related to specific environmental or health endpoints.

In the absence of quantitative assessments of external costs arising from environmental *and* human exposure to PFOA and its salts, accounting for long-term environmental and health impacts and damage costs, conclusions about social costs and benefits of risk management measures are currently not possible. This hampers a transparent comparison of the damage potential for PFOA and its salts in relation to other (persistent) chemicals. Moreover, risk management decisions based on economic costs reflect social costs of PFOA use (or social benefits of PFOA abatement) only partially, if at all. Hence, there is an urgent need to fill this gap. This is not primarily a problem of data availability. Rather, what is needed is first to develop integrated frameworks that allow transforming information about physico-chemical properties, environmental distribution, uses and exposure pathways of PFOA and its salts into impact information.

Due to their persistence, PFOA and its salts are stock pollutants, and hence impacts arise from the stock in different environmental media. Analyses of impacts and damage costs must, therefore, start with an assessment of the time-path of pollution for these media. Though the quantification of environmental pollution stocks has a long tradition in the environmental economics literature – e.g. regarding the optimal control of greenhouse gas emissions – the relevant approaches have not been applied to impact assessment for PFOA and its salts. An economic assessment that ignores stock dynamics is, thus, likely to significantly underestimate external and, hence, social costs of a continued use (or expected avoided costs of a restricted use) because "late damages" are ignored. Hence, in a regulatory context, including the time-path of pollution is indispensable for a coherent assessment of social costs that adequately reflect the concerns of PFOA and its salts. Though a method for quantifying stock dynamics in different media has become available, its application to PFOA and its salts, and an analysis of the implications of accounting for stock pollution properties for regulatory decisions, requires further research.

A monetisation of health and environmental impacts from PBT substances in general, and from PFOA and its salts in particular, is still in its infancy. For , estimates of (avoidable) economic costs have been provided for Assuming that valuation studies revealing peoples' preferences regarding the avoidance of impacts may be too challenging because current knowledge about impacts is still highly incomplete (ECHA, 2016[81]), a promising "second-best" option is to approximate the damage potential of PFOA and its salts by means of integrated modelling, combining environmental with economic methods. Though such an approach cannot overcome uncertainties inherent to data, and may therefore not reflect the "true" costs of PFOA use (or the benefits of abatement), it offers a transparent basis for decision-making that is coherent. In addition, it allows for analysing the impact of uncertainties and for updating the assessment in case further information becomes available.

Finally, besides method development, there is a need for capacity building at the level of decision-making institutions, e.g. national competent authorities and regulatory agencies. In particular, due to the complex properties and exposure pathways of PBT and vPvB substances such as PFOA (but also many others), the resulting pollution problems are complex. An assessment of social costs must, therefore, combine expertise from different disciplines, including toxicology and eco-toxicology, economics and statistics. This requires, ultimately, a trans-disciplinary collaboration between scientists and decision makers.

References

Ackerman, F. and R. Massey (2006), *The Economics of Phasing Out PVC -- Revised version*, Global Development and Environment Institute, Tufts University, http://www.ase.tufts.edu/gdae/Pubs/rp/Economics_of_PVC_revised.pdf. [99]

Alberini, A. (2017), "Measuring the economic value of the effects of chemicals on ecological systems and human health", *OECD Environment Working Papers*, No. 116, OECD Publishing, Paris, http://dx.doi.org/10.1787/9dc90f8d-en. [83]

Annys, E. (2016), *Challenges in applying SEA to assess applications for authorisation and restrictions, how would the system function without SEA?*, European Commission, Brussels, https://echa.europa.eu/-/workshop-on-socio-economic-analysis-in-applications-for-authorisation-and-restrictions-under-reach. [30]

Belanger, S. et al. (2017), "Future needs and recommendations in the development of species sensitivity distributions: Estimating toxicity thresholds for aquatic ecological communities and assessing impacts of chemical exposures", *Integrated Environmental Assessment and Management*, Vol. 13/4, pp. 664-674, http://dx.doi.org/10.1002/ieam.1841. [79]

Bengyuzov, M. (2016), *SEA and its Role in Decision-Making*, European Commission, Brussels, https://echa.europa.eu/documents/10162/22816069/sea_decision-making_process_bengyuzov_en.pdf/667fa47d-2952-4f6a-a91d-5f7b2beb2b50. [28]

Bernier, J. et al. (2014), *Effectiveness of Conventional and Advanced In Situ Leachate Treatment*, Environment Canada, Québec, http://chm.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC12/POPRC12Followup/PFOAInfo/tabid/5453/Default.aspx. [36]

Bogaert, S. (2012), *Valuation of the results of the Environmental Impact Assessment project -- 2012*, National Institute for Public Health and the Environment, Bilthoven. [92]

Camboni, M. et al. (2016), *Study on the Calculation of the Benefits of Chemicals Legislation on Human Health and the Environment Development of a System of Indicators Final Report*, European Commission, Brussels, http://dx.doi.org/10.2779/034894. [80]

Chiu, W. (2017), "Chemical risk assessment and translation to socio- economic assessments", *OECD Environment Working Papers*, No. 117, OECD Publishing, Paris, http://dx.doi.org/10.1787/a930054b-en. [84]

Cousins, I. et al. (2016), "The precautionary principle and chemicals management: The example of perfluoroalkyl acids in groundwater", *Environment International*, Vol. 94, pp. 331-340, http://dx.doi.org/10.1016/j.envint.2016.04.044. [16]

Dubourg, R. (2016), *The role of socio-economic analysis in compiling an application for authorisation -- A practitioner's view*, European Commission, Brussels, https://echa.europa.eu/-/workshop-on-socio-economic-analysis-in-applications-for-authorisation-and-restrictions-under-reach. [32]

ECETOC (2008), *Counting the Costs and Benefits of Chemical Controls: Role of Environmental Risk Assessment in Socio-Economic Analysis*, European Centre for Ecotoxicology and Toxicology of Chemicals, Brussels, http://www.ecetoc.org/wp-content/uploads/2014/08/ECETOC-WR-13-Counting-the-costs-benefits-of-chemical-controls-role-of-environmental-risk-assessment-in-socio-economic-analysis-.pdf. [97]

ECETOC (2011), *Environmental Impact Assessment for Socio-Economic Analysis of Chemicals: Principles and Practice*, European Centre for Ecotoxicology and Toxicology of Chemicals, Brusseles, http://www.ecetoc.org/wp-content/uploads/2014/08/ECETOC-TR-113-Environmental-impact-assessment-for-socio-economic-analysis-of-chemicals-.pdf. [93]

ECETOC (2015), *Chemical Risk Assessment -- Ecosystem Services*, European Centre for Ecotoxicology and Toxicology of Chemicals, Brussels, http://www.ecetoc.org/wp-content/uploads/2016/04/ECETOC-TR-125-Chemical-Risk-Assessment-Ecosystems-Services.pdf. [88]

ECHA (2008), *Guidance on Socio-Economic Analysis – Restrictions*, European Chemicals Agency, Helsinki, https://echa.europa.eu/documents/10162/23036412/sea_restrictions_en.pdf/2d7c8e06-b5dd-40fc-b646-3467b5082a9d. [9]

ECHA (2011), *Guidance on the preparation of socio economic analysis as part of an application for authorisation*, European Chemicals Agency, Helsinki, https://echa.europa.eu/documents/10162/13643/authorisation_application_en.pdf. [7]

ECHA (2013), *Support Document for the identification of pentadecafluorooctanoic acid (PFOA) as a substance of very high concern because of its CMR and PBT properties*, European Chemicals Agency, Helsinki, https://echa.europa.eu/documents/10162/8059e342-1092-410f-bd85-80118a5526f5. [25]

ECHA (2013), *Support Document for identification of Ammonium pentadecafluorooctanoate (APFO) as a substance of very high concern because of its CMR and PBT properties*, European Chemicals Agency, Helsinki, https://echa.europa.eu/documents/10162/5e2c1e53-be98-4104-8b96-9cd88655a92a. [26]

ECHA (2014), *Annex XV Restriction Report. Proposal for a Restriction -- Perfluorooctanoic acid (PFOA), its salts and PFOA-related substances*, European Chemicals Agency, Helsinki, https://echa.europa.eu/documents/10162/e9cddee6-3164-473d-b590-8fcf9caa50e7. [27]

ECHA (2015), *Background document to the Opinion on the Annex XV dossier proposing restrictions on perfluorooctanoic acid (PFOA), PFOA salts and PFOA-related substances*, European Chemicals Agency, Helsinki. [12]

ECHA (2015), *Background document to the Opinion on the Annex XV dossier proposing restrictions on perfluorooctanoic acid (PFOA), PFOA salts and PFOA-related substances*, European Chemicals Agency, Helsinki. [40]

ECHA (2016), *Evaluation of restriction reports and applications for authorisation for PBT and vPvB substances in SEAC*, European Chemicals Agency, Helsinki. [81]

ECHA (2016), *Valuing selected health impacts of chemicals -- Summary of the Results and a Critical Review of the ECHA study*, ECHA, Helsinki, https://echa.europa.eu/support/socio-economic-analysis-in-reach/willingness-to-pay-to-avoid-certain-health-impacts. [86]

ECHA (2017), *Guidance on Information Requirements and Chemical Safety AssessmentsChapter R.11: PBT/vPvB Assessment.*, ECHA, Helsinki, http://dx.doi.org/10.2823/128621. [73]

Environment and Climate Change Canada (2006), *Perfluorooctane and its Salts and Certain Other* [35]

Compounds Regulations: Regulatory Impact Analysis Statement -- 2006, Environment and Climate Change Canada, Ottawa, http://publications.gc.ca/gazette/archives/p1/2006/2006-12-16/pdf/g1-14050.pdf#page=53.

Environment and Climate Change Canada (2017), *PFCAs and their precursors in perfluorinated products: Environmental agreement overview*, http://www.ec.gc.ca/epe-epa/default.asp?lang=En&n=AE06B51E-1[(accessed on 16 October 2017). [18]

Environment Canada (2016), *Regulations Amending the Prohibition of Certain Toxic Substances Regulations (2012)*, Canada Gazette, http://www.gazette.gc.ca/rp-pr/p2/2016/2016-10-05/html/sor-dors252-eng.php#archived. [45]

European Commission (2006), *Regulation (EC) No. 1907/2006 of the European Parliament and the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)*. [6]

European Commission (2008), *Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures*, Official Journal of the European Union, http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008R1272-20170101&from=EN. [24]

European Commission (2014), *Commission Regulation (EU) No 317/2014 of 27 March 2014 amending Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards Annex XVII (CMR substances)*, Official Journal of the European Union, http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0317&from=EN. [23]

EUSES (2008), *The European Union System for the Evaluation of Substances - European Commission*, https://ec.europa.eu/jrc/en/scientific-tool/european-union-system-evaluation-substances (accessed on 03 August 2017). [71]

Falk, I. and R. Mendelsohn (1993), "The Economics of Controlling Stock Pollutants: An Efficient Strategy for Greenhouse Gases", *Journal of Environmental Economics and Management*, Vol. 25/1, pp. 76-88. [58]

Fenner, K. et al. (2005), "Comparing estimates of persistence and long-range transport potential among multimedia models", *Environmental Science and Technology*, Vol. 39/7, pp. 1932-1942, http://dx.doi.org/10.1021/es048917b. [52]

Fleming, R., R. Adams and C. Kim (1995), "Regulating Groundwater Pollution: Effects of Geophysical Response Assumptions on Economic Efficiency", *Water Resources Research*, Vol. 31/4, pp. 1069-1076, http://dx.doi.org/10.1029/94WR03287. [59]

FluoroCouncil (2016), *Form for submission of information specified in Annex F of the Stockholm Convention pursuant to Article 8 of the Convention*, FluoroCouncil, Washington, DC, http://chm.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC12/POPRC12Followup/PFOAInfo/tabid/5453/Default.aspx. [46]

Forster, B. (1975), "Optimal pollution control with a nonconstant exponential rate of decay", *Journal of Environmental Economics and Management*, Vol. 2/1, pp. 1-6, http://dx.doi.org/10.1016/0095-0696(75)90016-9. [57]

Gabbert, S. and H. Weikard (2010), "A theory of chemicals regulation and testing", *Natural Resources Forum*, Vol. 34/2, pp. 155-164, http://dx.doi.org/10.1111/j.1477-8947.2010.01300.x. [49]

Gabbert, S. et al. (2014), "Socio-economic analysis for the authorisation of chemicals under REACH: A case of very high concern?", *Regulatory Toxicology and Pharmacology*, Vol. 70/2, [8]

pp. 564-571, http://dx.doi.org/10.1016/j.yrtph.2014.08.013.

Gabbert, S. and M. Nendza (2014), *Authorisation of chemicals in REACH: A stock-pollution approach to assessing impacts of persistent chemicals in a socio-economic analysis -- Part I*, Luxemburg Environment Agency, Wageningen. [1]

Gabbert, S. and M. Nendza (2015), *Authorisation of chemicals in REACH: A stock-pollution approach to assessing impacts of persistent chemicals in a socio-economic analysis -- Part II -- Simulation of multimedia stock dynamics*, Luxemburg Environment Agency, Wageningen. [2]

Gabbert, S. and I. Hilber (2016), "Time matters: A stock-pollution approach to authorisation decision-making for PBT/vPvB chemicals under REACH", *Journal of Environmental Management*, Vol. 183, pp. 236-244, http://dx.doi.org/10.1016/j.jenvman.2016.08.038. [34]

Gabbert, S., M. Nendza and H. Stolzenberg (2016), "Zur Erfassung von Langzeit-Auswirkungen von PBT and vPvB Stoffen im Rahmen der sozio-ökonomischen Analysen in REACH", *Mitteilungen der Fachgruppe Umweltchemie und Ökotoxikologie*, Vol. 22/1, https://www.gdch.de/fileadmin/downloads/Netzwerk_und_Strukturen/Fachgruppen/Umweltchemie_OEkotoxikologie/mblatt/2016/heft116.pdf, pp. 3-7. [70]

Gabbert, S. et al. (2017), *A benchmark-level approach for evaluating PBT and vPvB chemicals in REACH authorisation and restriction procedures -- Poster presented at the 27th Setac Europe Annual Meeting*. [76]

Gabbert, S. et al. (2018), *Approach for Evaluation to PBTs Subject to Authorisation and Restriction Procedures in the Context of Socio-Economic Analysis*, European Commission, http://dx.doi.org/10.2873/33669. [69]

Gould, E. (2009), "Childhood lead poisoning: Conservative estimates of the social and economic benefits of lead hazard control", *Environmental Health Perspectives*, Vol. 117/7, pp. 1162-1167, http://dx.doi.org/10.1289/ehp.0800408. [44]

Greßmann, A. et al. (2014), *Socio-Economic Analysis (SEA) in authorisation and restriction under REACH: Assessment of abatement costs of chemicals – ex ante and ex post -- Final Report*, German Federal Environment Agency, Dessau, http://www.bmub.bund.de/fileadmin/Daten_BMU/Pools/Forschungsdatenbank/fkz_3711_65_407_reach_analyse_bf.pdf. [42]

Hart, R. and M. Brady (2002), "Nitrogen in the Baltic Sea -- policy implications of stock effects", *Journal of Environmental Management*, Vol. 66, pp. 91-103, http://dx.doi.org/10.1006/jema.2002.0579. [60]

Hök, F. (2016), *Socio-Economic Analysis in REACH*, European Commission, Brussels, https://echa.europa.eu/documents/10162/22816069/sea_reach_hok_en.pdf/0d611d9e-d995-47ee-b4a2-e08677d4e2bc. [29]

Jongeneel, W. et al. (2014), *Health Impact Assessment in REACH restriction dossiers Development of a structured HIA format*, National Institute for Public Health and the Environment, Bilthoven, http://www.rivm.nl/bibliotheek/rapporten/2014-0032.pdf. [89]

Keeler, E., M. Spence and R. Zeckhauser (1972), "The optimal control of pollution", *Journal of Economic Theory*, Vol. 4/1, pp. 19-34, http://dx.doi.org/10.1016/0022-0531(72)90159-7. [56]

Klasmeier, J. et al. (2006), "Application of multimedia models for screening assessment of long-range transport potential and overall persistence", *Environmental Science and Technology*, Vol. 40/1, pp. 53-60, http://dx.doi.org/10.1021/es0512024. [53]

Kolstad, C. (1996), "Learning and Stock Effects in Environmental Regulation: The Case of Greenhouse Gas Emissions", *Journal of Environmental Economics and Management*, Vol. 31/1, pp. 1-18, http://dx.doi.org/10.1006/jeem.1996.0028. [65]

Krishnan, N. and A. Raflka Smati (2003), *Alternatives to Reduce Perfluorinated Compound (PFC) Emissions From Semiconductor Dielectric Etch Processes: Meeting Environmental Commitments While Minimizing Costs*. [38]

Li, L. et al. (2016), "Long-term emissions of hexabromocyclododecane as a chemical of concern in products in China", *Environment International*, Vol. 91, pp. 291-300, http://dx.doi.org/10.1016/j.envint.2016.03.007. [74]

Loveless, S. et al. (2006), "Comparative responses of rats and mice exposed to linear/branched, linear, or branched ammonium perfluorooctanoate (APFO)", *Toxicology*, Vol. 220/2, pp. 203-217, http://dx.doi.org/10.1016/j.tox.2006.01.003. [13]

Mackay, D. and S. Paterson (1991), "Evaluating the Multimedia Fate of Organic Chemicals: A Level III Fugacity Model", *Environmental Science & Technology* , Vol. 25, pp. 427-436. [50]

Mackay, D. (2001), *Multimedia Environmental Models: The Fugacity Approach*, CRC Press, Taylor & Francis Group. [67]

Malits, J. et al. (2017), "Perfluorooctanoic acid and low birth weight_ Estimates of US attributable burden and economic costs from 2003 through 2014", *International Journal of Hygiene and Environmental Health*, pp. 1-0, http://dx.doi.org/10.1016/j.ijheh.2017.11.004. [43]

Navrud, S. (2017), "Possibilities and challenges in transfer and generalisation of monetary estimates for environmental and health benefits of regulating chemicals", *OECD Environment Working Papers*, No. 119, OECD, Paris, http://dx.doi.org/10.1787/95c2b371-en. [85]

Newell, R. and W. Pizer (2003), "Regulating stock externalities under uncertainty", *Journal of Environmental Economics and Management*, Vol. 45, pp. 416-432, http://dx.doi.org/10.1016/S0095-0696(02)00016-5. [66]

Nordhaus, W. (1992), "An Optimal Transition Path for Controlling Greenhouse Gases", *Science* 5086, pp. 1315-1319, http://dx.doi.org/10.1126/science.258.5086.1315. [61]

Nordhaus, W. (1993), "Optimal Greenhouse-Gas Reductions and Tax Policy in the DICE Model", *Source: The American Economic Review*, Vol. 83/2, http://www.jstor.org/stable/2117683, pp. 313-317. [63]

Nordhaus, W. (1993), "Rolling the 'DICE' -- An optimal transition path for controlling greenhouse gases", *Resource and Energy Economics*, Vol. 15/1, pp. 27-50. [62]

OECD (1992), *Report of the OECD Workshop on Extrapolation of Laboratory Aquatic Toxicity Data to the Real Environment*, OECD, Paris, http://www.oecd.org/chemicalsafety/testing/34528236.pdf. [77]

OECD (2000), *Guidance for conducting retrospective studies on socio-economic analysis*, OECD, Paris, http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=env/jm/mono(99)27. [4]

OECD (2000), *Framework for integrating socio-economic analysis in chemical risk management and decision-making*, OECD, Paris, http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=env/jm/mono(2000)5. [5]

OECD (2002), *Technical Guidance Document on the use of socio-economic analysis in chemical risk management decision making*, OECD, Paris, http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=env/jm/mono(2002)10. [3]

OECD (2013), "Synthesis paper on per-and polyfluorinated chemicals (PFCs)", *OECD Environment, Health and Safety Publications*, OECD, Paris, http://www.oecd.org/chemicalsafety/risk-management/synthesis-paper-on-per-and-polyfluorinated-chemicals.htm. [11]

OECD (2015), "Risk reduction approaches for PFASs", *OECD Environment, Health and Safety Publications -- Series on Risk Management*, No. 29, OECD, Paris, https://www.oecd.org/chemicalsafety/risk-management/Risk_Reduction_Approaches%20for%20PFASS.pdf. [15]

Olsson, I. (2014), *The Cost of Inaction: A Socioeconomic analysis of costs linked to effects of endocrine disrupting substances on male reproductive health*, Nordic Council of Ministers, Copenhagen. [90]

Oosterhuis, F. and R. Brouwer (2015), *Benchmark development for the proportionality assessment of PBT and vPvB substances*, Institute for Environmental Studies, VU University Amsterdam, https://echa.europa.eu/documents/10162/13647/R15_11_pbt_benchmark_report_en.pdf/a695a7fd-e2bd-4dc5-b69a-bc02f9f98fef. [41]

Pedersen, F. et al. (2005), *The impact of REACH on the environment and human health*, European Commission, DG Environment, http://www.dhi.dk. [98]

Péry, A. et al. (2013), "Perspectives for integrating human and environmental risk assessment and synergies with socio-economic analysis", *Science of the Total Environment*, Vol. 456-457, pp. 307-316, http://dx.doi.org/10.1016/j.scitotenv.2013.03.099. [33]

Plourde, C. (1972), "A Model of Waste Accumulation and Disposal", *The Canadian Journal of Economics*, Vol. 5/1, http://www.jstor.org/stable/133997, pp. 119-125. [55]

Rabl, A. and M. Holland (2008), "Environmental Assessment Framework for Policy Applications: Life Cycle Assessment, External Costs and Multi-criteria Analysis", *Journal of Environmental Planning and Management*, Vol. 51/1, pp. 81-105, http://dx.doi.org/10.1080/09640560701712275. [47]

Radaelli, C. (2009), "Measuring policy learning: regulatory impact assessment in Europe", *Journal of European Public Policy*, Vol. 16/8, pp. 1145-1164, http://dx.doi.org/10.1080/13501760903332647. [10]

Rheinberger, C. (2016), *Dispelling the Myths of Socio-Economic Analysis*, European Commission, Brussels, https://echa.europa.eu/-/workshop-on-socio-economic-analysis-in-applications-for-authorisation-and-restrictions-under-reach. [31]

Rijk, I., M. van Duursen and M. van den Berg (2016), *Health costs that may be associated with Endocrine Disrupting Chemicals*, Institute for Risk Assessment Sciences, University Utrecht, the Netherlands, https://www.uu.nl/sites/default/files/rijk_et_al_2016_-_report_iras_-_health_cost_associated_with_edcs_3.pdf. [87]

RPA et al. (2011), *Assessing the Health and Environmental Impacts in the Context of Socio-economic Analysis Under REACH Final Report Part 1: Literature Review and Recommendations*, European Commission, DG Environment, https://echa.europa.eu/documents/10162/13580/reach_sea_part1_en.pdf. [95]

RPA et al. (2012), *Assessment of the Health and Environmental Benefits of REACH -- Part A -- Methodology*, European Commission, DG Environment, http://www.rpaltd.co.uk. [94]

Scheringer, M. et al. (2004), "The Effect of Export to the Deep Sea on the Long-Range Transport Potential of Persistent Organic Pollutants", *Environmental Science and Pollution Research* , Vol. 11/1, pp. 41-48, http://dx.doi.org/10.1065/esor2003.11.176. [51]

Schuur, A. et al. (2008), *Health impact assessment of policy measures for chemicals in non-food consumer products*, RIVM, Bilthoven, http://www.rivm.nl/bibliotheek/rapporten/320015001.pdf. [96]

Smith, V. (1972), "Dynamics of Waste Accumulation: Disposal versus Recycling", *The Quarterly Journal of Economics*, Vol. 86/4, pp. 600-616. [54]

Sørensen, M. et al. (2016), *Valuation Literature on Chemicals: A Description of an Inventory of Valuation Literature on Chemicals*, Nordic Council of Ministers, Copenhagen, http://dx.doi.org/10.6027/NA2017-903. [48]

Stockholm Convention (2017), *PFOA, its salts and PFOA-related compounds: Draft risk management evaluation*, Stockholm Convention, Stockholm, http://www.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC12/POPRC12Followup/tabid/5339/Default.aspx. [14]

Ulph, A. and D. Ulpht (1994), "The optimal time path of a carbon tax", *Oxford Economic Papers*, Vol. 46, pp. 857-868. [64]

UNEP (2012), *Technical paper on the identification and assessment of alternatives to the use of perfluorooctane sulfonic acid in open applications*, UNEP, Geneva, http://www.subsport.eu/wp-content/uploads/2012/11/UNEP-POPS-POPRC.8-INF-17.English.pdf. [39]

US EPA (2006), *Letter Inviting Participation in the PFOA Stewardship Program*, US EPA, Washington, DC, https://www.epa.gov/sites/production/files/2015-10/documents/dupont.pdf. [19]

US EPA (2008), *EPI Suite™ -- Estimation Program Interface | Predictive Models and Tools for Assessing Chemicals under the Toxic Substances Control Act (TSCA)*, https://www.epa.gov/tsca-screening-tools/epi-suitetm-estimation-program-interface (accessed on 03 August 2017). [72]

US EPA (2013), *Assessing and Managing Chemicals under TSCA. Risk Management for Per- and Polyfluoroalkyl Substances (PFASs) under the TSCA*, https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-and-polyfluoroalkyl-substances-pfass (accessed on 03 August 2017). [21]

US EPA (2015), *Long-Chain Perfluoroalkyl Carboxylate and Perfluoroalkyl Sulfonate Chemical Substances; Significant New Use Rule*, Federal Register, https://www.federalregister.gov/documents/2015/03/16/2015-05958/long-chain-perfluoroalkyl-carboxylate-and-perfluoroalkyl-sulfonate-chemical-substances-significant. [22]

US EPA (2017), *Fact Sheet: 2010/2015 PFOA Stewardship Program*, https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program (accessed on 02 August 2017). [20]

Verhoeven, J. et al. (2012), *From risk assessment to environmental impact assessment of chemical substances*, http://www.rivm.nl/bibliotheek/rapporten/601353002.pdf. [91]

Vierke, L. et al. (2012), "Perfluorooctanoic acid (PFOA) — main concerns and regulatory developments in Europe from an environmental point of view", *Environmental Sciences* [17]

Europe, Vol. 24, https://doi.org/10.1186/2190-4715-24-16.

Webster, E. et al. (2005), *Development and Application of Models of Chemical Fate in Canada: Modelling Guidance Document*, Environment Canada, Peterborough, http://www.trentu.ca/academic/aminss/envmodel/CEMNReport200501.pdf. [68]

Wenzel, A. et al. (2015), *Revision der Umweltqualitätsnormen der Bundes-Oberflächengewässerverordnung nach Ende der Übergangsfrist für Richtlinie 2006/11/EG und Fortschreibung der europäischen Umweltqualitätsziele für prioritäre Stoffe*, German Federal Environment Agency, Dessau, http://www.umweltbundesamt.de/publikationen/revision-der-umweltqualitaetsnormen-der-bundes. [78]

Wolf, K. (2011), *Developing a California Inventory for Industrial Applications of Perfluorocarbons, Sulfur Hexafluoride, Hydrofluorocarbons, Nitrogen Trifluoride, Hydrofluoroethers and Ozone Depleting Substances*, The California Air Resources Board, Los Angeles, http://chm.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC12/POPRC12Followup/PFOAInfo/tabid/5453/Default.aspx. [37]

Xu, Z. (2015), *Uncertain Multi-Attribute Decision Making*, Springer, Heidelberg, http://dx.doi.org/10.1007/978-3-662-45640-8. [82]

Zhu, J. et al. (2016), "Socio-economic analysis of the risk management of hexabromocyclododecane (HBCD) in China in the context of the Stockholm Convention", *Chemosphere*, Vol. 150, pp. 520-527, http://dx.doi.org/10.1016/j.chemosphere.2015.11.007. [75]