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Environmental Assessment of Dry Photovoltaic Etching

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Abstract

The report is summarizing the research contributions from VF as partner in the EU-project "Development of a competitive zero Global Warming Potential (GWP) dry process to reduce the dramatic water consumption in the ever expanding solar cell manufacturing industry – SOLNOWAT".

In the project a new etching method for silicon crystalline solar cell wafers was developed. VF was responsible for two main parts of the project: 1) Compiling an overview of laws and regulatory requirements relevant for the new etching process, and 2) Conducting simplified life cycle assessment (LCA) of the dry chemical etching in comparison with current state of the art wet chemical etching.

The overview of the regulatory framework was established through compiling up-to-date European and global emission regulations and requirements. This included a detailing of forthcoming regulations.

The simplified LCA of the dry process gave as result a potential for a substantial reduction in water consumption, i.e. 85 % reduction in comparison with the wet acidic etching, and 89 % reduction in comparison with the alkaline wet etching. The emissions of climate (green house) gases were also determined to be reduced, with 63 % and 20 % respectively, when compared with current state of the art wet acidic and alkaline chemical etching. The toxicity impacts were assessed to be lower for the dry chemical etching, compared to the wet process, allthough the uncertainty was quite high for that impact category.

Other publications from the project

Andersen, Otto. 2013. *Unintended Consequences of Renewable Energy*. *Problems to be Solved.* London: Springer.

Andersen O (2013) Solar Cell Production. In: Unintended Consequences of Renewable Energy. Problems to be Solved. Springer, London, pp 81–89.

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Preface

The SOLNOWAT project was funded by the European Commisssion through the 7th Framework Programme for Research and Technology Development, through the funding scheme "Capacities: Research for the benefit of SMEs"', and managed by REA - Research Executive Agency (http://ec.europa.eu/research/rea) under grant agreement no. 286658.

The project was coordinated by ULTRA HIGH VACUUM SOLUTIONS LIMITED / Nines Engineering. The other SMEs was the Czech solar cell manufacturer Solartec, the French company Alyxan that developes technology for gas analysis and the German firm Zimmermann & Schilp Handhabungstechnik that develops wafer handling systems for the process. The providers of RTD also included the two German Fraunhofer Institutes ISE and IWS in addition to Vestlandsforsking.

Researcher dr. Otto Andersen has been the project manager at Vestlandsfrosking and he has written the main parts of this report. He was also responsible for the compilation of regulatory requirements. Researcher Geoffrey Gilpin performed the SIMAPRO work in the life cycle assessment.

We want to thank the project partners and in particular the project coordinator Laurent Clochard at Nines Engineering for an excellent dialogue throughout the project period and valuable ideas and feedback to the project.

Vestlandsforsking, April 2014

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Summary

This report is summarizing the results of research conducted by VF on environmental issues connected to production of photovoltaic (PV) solar cells. The bulk of this research was carried out through the EU-project "Development of a competitive zero Global Warming Potential (GWP) dry process to reduce the dramatic water consumption in the ever expanding solar cell manufacturing industry – SOLNOWAT".

In the introduction of this report we present some problematic environmental aspects of current wet chemical solar cell production. The high water consumption for rinsing of wafers between multible etching steps in chemical batchs is a key reason why new etching technologies need to be developed. Toxicity and explosion hazards are other issues that characterize PV production. The glimate gas emissions during the etching is a key factor contributing to the poor life-cycle performance of current solar cells in comparison with other technologies for converting renewable energy into electricity.

The new etching process that has been developed in the SOLNOWAT project is takes place in dry conditions with the use of fluorine gas to obtain the desired structure of the wafers. This is of concern, because fluorine is a very toxic gas. Therefore it was important to obtain an overview of regulatory requirements for this nes production process. VF was responsible for compiling such an overview, which contains emission and exposure limits for the main types of emissions to air and water from the new process. The overview was established through compiling up-to-date European and global emission regulations and requirements. This also included some consideration regarding potential forthcoming regulations.

The second task for VF in the project was to conduct a simplified life-cycle assessment (LCA) of the dry chemical etching process, in comparison with current state of the art wet chemical etching. This work gave as result that there is a substantial potential for reducing the water consumption by converting to the dry process. The LCA indicated that as much as 85 % of the water use could be saved in comparison with the current wet acidic etching, and a 89 % reduction in comparioson with the alkaline wet etching.

The LCA gave as result that the emissions of climate (green-house) gases could be reduced by 63 % and 20 % respectively, when compared with current state of the art wet acidic and alkaline chemical etching. Even the toxicity impacts were assessed to be lower for the dry chemical etching, compared to the wet process, allthough the uncertainty was quite high for that impact category.

Sammendrag

Denne rapporten oppsummerer resultatene av forskning utført av VF omkring miljøproblemer knyttet til produksjon av photovoltaiske (PV) solceller. Det meste av denne forskningen ble utført i EU - prosjektet "Development of a competitive zero Global Warming Potential (GWP) dry process to reduce the dramatic water consumption in the ever expanding solar cell manufacturing industry – SOLNOWAT ".

Innledningsvis går denne rapporten gjennom noen problematiske miljøaspekter ved dagens våtkjemiske produksjon av solceller. Det høye vannforbruket til skylling av wafere mellom de mange etsetrinnene i kjemikaliebad er en viktig grunn til utvikling at ny etseteknologi. Toksisitet og eksplosjonsfare er andre problemer knyttet til dagens PV produksjon. Utslipp av klimagasser fra etsningen er en hovedgrunn til at dagens solceller kommer relativt dårlig ut i sammenligning med andre teknologier for å konvertere fornybar energi til elektrisitet når hele livssyklusen tas hensyn til.

Den nye etseprosessen som er blitt utviklet i SOLNOWAT-prosjektet er basert på tørrkjemisk behandling med bruk av fluorgass for å oppnå den ønskede struktur på solcellewaferene. Dette kan være problematisk, fordi fluorgass er svært giftig. Derfor var det i prosjektet viktig å få en oversikt over lover og regler knyttet til denne produksjonsprosessen. VF var ansvarlig for å utarbeide en slik oversikt, som inneholder utslipps- og eksponeringsgrenser for de viktigste typer utslipp til luft og vann fra den nye prosessen. Oversikten ble etablert gjennom å gjennomgå oppdaterte europeiske og globale utslippsforskrifter og -krav. Dette inkluderte også noen vurdering om mulige kommende regelverk, som er tatt med i rapporten.

Den andre oppgaven for VF i prosjektet var å gjennomføre en forenklet livsløpsvurderinger (LCA) av den tørre kjemisk etsing prosessen, sammenlignet med dagens våtkjemiske etsing. Dette arbeidet ga som resultat at det er et betydelig potensial for å redusere vannforbruket ved å gå over til den tørre prosessen. LCA-resultatene indikerte at så mye som 85% av vannforbruket kan bli spart, sammenlignet med nåværende våtkjemiske syrebaserte etsing, og en 89% reduksjon i sammenlikning med alkalisk våtkjemisk etsing.

Den utførte LCA ga som resultat at utslippene av klimagasser kan reduseres med 63 % og 20 %, i sammenlikning med dagens syrebaserte våtkjemiske og alkalisk våtkjemisk etsing, henholdsvis. Til og med toksisitetsvurderingene ga bedre resultat for tørrkjemisk etsing, selv om usikkerheten var ganske høy for denne miljøbelastningskategorien.

List of Abbreviations

AAC	Acceptable ambient concentration
AC	Air contaminant
ACGIH	American Conference of Governmental Industrial Hygienists
ASIL	Acceptable source impact level
BAT	Biologischer Arbeitsstoff-Toleranz-Wert (Biological tolerance value for occupational exposures)
BEI	Biological exposure index
BNA	Bureau of National Affairs
CDC	Center for Disease Control and Prevention
CDM	Clean development mechanism
CMP	Conference of the parties serving as the Meeting of the Parties
COP	Conference of the Parties
DB	Dichlorobenzene
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)
DWG	Drinking water guideline
DWS	Drinking water standard
EC	European Commission
EPA	U.S. Environmental Protection Agency
F^-	Fluoride
GHG	Greenhouse gas
GQS	Groundwater quality standard
GS	Groundwater standard
GWP	Global warming potential
H_2O_2	Hydrogen peroxide
H_2SiF_6	Fluorosilicic acid
HCFC-22	Hydrochlorofluorocarbon-22
HF	Hydrogen fluoride
HFC-23	Hydrofluorocarbon-23
HOF	Hypofluorous acid
HSDB	Hazardous Substances Data Bank
HTP	Haitalliseksi tunnetut pitoisuudet (Occupational exposure limits)
IDLH	Immediately dangerous to life or health
LCA	Life cycle assessment
MAK	Maximale Arbeitsplatz-Konzentration (Maximum workplace concentration)
MCL	Maximum contaminant level. Enforceable level, intended to prevent acute and chronic illness.
NF_3	Nitrogen trifluoride
NIOSH	National Institute of Occupational Safety & Health
O_3	Ozone
OEL	Occupational exposure limit
OF_2	Oxygen difluoride
OSHA	Occupational Safety & Health Administration
PEL	Permissible exposure limit
PPM	Parts per million

PQL	Practical quantification level
PV	Photovoltaic
REL	Recommended Exposure Limit. This refers to NIOSH time-weighted average (TWA) concentrations for up to a 10-hour workday during a 40-hour workweek.
RL	Reporting limit
SBSTA	Subsidiary Body for Scientific and Technological Advice (SBSTA)
SCHER	Scientific Committee on Health and Environmental Risk
SCOEL	Scientific Committee on Occupational Exposure Limits
SER	The Social and Economic Council of the Netherlands
SiO_2	Silicon oxide
SF_6	Sulphur hexafluoride
SMCL	Secondary maximum contaminant level.
SoA	State of the Art
STEL	Short-term exposure limit
TA	Technische Anleitung (technical guide)
TAP	Toxic air pollutant
TLV	Threshold limit value
TWA	Time-weighted average
UNFCCC	United Nations Framework Convention on Climate Change
VDI	Verein Deutscher Ingenieure (Association of German Engineers)

1 Introduction

1.1 The problematics of current solar cell production

Solar photovoltaic cells (PV) are widely admired for the way they silently, and seemingly without pollution, extract clean energy from the sun's rays. However, this is by no means the full picture, as the production of the solar cells contribute to specific environmental problems (Andersen 2013). There exist serious environmental issues connected not only to the way PV solar cell panels are currently manufactured, but also to the way they are disposed of at the end of their use phase (Zehner 2011).

1.1.1 The high water consumption

A key problem with current PV cell production, is the high water consumption in the etching of the crystalline silicon wafers. The wet chemical process, which is State of the Art (SoA) in PV cell production, involves the processing of the wafers in a series of consecutive and different chemical baths. Between each chemical treatment, the wafers need to be rinsed free from chemicals, using tens of thousands of liters of clean water in the process. In 2011, a leading USA solar company with manufacturing plants in Malaysia and the Philippines stated that their wet chemical-based process required about 15000 liters of high purity process water per minute for a 1.4 GW production facility for PV solar cells (Duffy 2012).

As such, major chemical waste treatment facilities are necessary to cope with the large volumes of contaminated water from the PV solar cell production when using the wet chemical process (Agostinelli et al. 2004). That is why alternative process types, using less water, are needed.

1.1.2 The toxicity and explosion hazard

The manufacturing of PV cells relies on the use of a large number of different toxic chemicals and explosive compounds (Phylipsen and Alsema 1995; Kuemmel et al. 1997). Therefore, PV cell production in general, has potential hazardous impacts, from the chemicals being released during the various process steps, like volatile organic substances during panel laminating (Phylipsen and Alsema 1995). In addition, accidents connected to the operation of the factories, can lead to severe health consequences for workers in the manufacturing facilities, as well as for local residents.

1.1.3 The climate gas emissions

The PV manufacturing industry is in addition one of the leading emitters of fluorinated compounds. This includes hexafluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulphur hexafluoride (SF_6). These are all extremely strong greenhouse gases, with global warming potentials (GWPs) of 12,200, 17,200, and 22,800 times that of CO_2 on a 100 year time horizon (Forster et al. 2007).

The use of SF_6 is for example commonly used to remove damages to the wafers, so-called saw damages, that have occurred during the slicing of the crystalline silicon ingots[1]. The SF_6 is also used during the oxide etching process step (Piechulla et al. 2011). The use of these strong greenhouse gases implies that an unintended effect of massive implementation of PV solar cells in the future is a considerable impact on climate, from their manufacturing phase (Alsema 2000; Alsema and de Wild-Scholten 2005; Fthenakis et al. 2008; Fthenakis and Kim 2010). This is in addition to the fact that production of silicon for crystalline PV solar cells also contributes substantially to the emission of GHGs (Pehnt 2006). These aspects explain why electricity production with the use of PV solar cells is worse than many other technologies, in terms of life cycle GHG emissions. Rather detrimental life cycle performance have been reported, with emissions as high as 110 g CO_{2eq}/kWh (Jungbluth 2005; Fthenakis et al. 2008). In the European Commission ExternE project on external costs for energy the life-cycle emissions from PV installations in Germany were presented to be as high as 180 g CO_{2eq}/kWh (EC 2003; Fthenakis and Kim 2007). In ExternE the use of PV solar cells was ranked even worse than natural gas in terms of life cycle GHG emissions and air pollution (EC 1995; EC 2003; Agostinelli et al. 2004).

1.1.4 Other environmental impacts

When the combined external costs from impacts related to noise, health, material and crops in the life cycle of technologies for German electricity generation options were compared, only lignite and coal was worse than PV, as shown in Table 1. The renewable energy technologies wind and hydro came out substantially better (EC 2003).

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[1] The ingot is a casted chunk of crystalline silicon that is made from a molten smelt. It is cut into thin slices that ends up as wafers after several steps of processing

Table 1 Life cycle external costs of electricity generation in Germany, expressed in € cent per kWh (EC 2003)

	Coal	**Lignite**	**Natural gas**	**Nuclear**	**PV**	**Wind**	**Hydro**
Noise	0	0	0	0	0	0.0050	0
Health	0.7300	0.9900	0.3400	0.1700	0.4500	0.0720	0.0510
Material	0.0150	0.0200	0.0070	0.0020	0.0120	0.0020	0.0010
Crops	0	0	0	0	0	0.0007	0.0002
Total	**0.7450**	**1.0100**	**0.3470**	**0.1720**	**0.4620**	**0.0797**	**0.0522**

In addition to the impacts described above, some of the materials entering into PV cells are of concern. One example is the use of fullerenes, such as C_{60}, also termed Buckminster fullerene[2] or in short Bucky balls. These carbon nanomaterials are used in certain new types of solar cells (Manzetti and Andersen 2012; Manzetti et al. 2013). A series of studies has been conducted into toxicological properties and potentials for other adverse health effects of fullerenes, with regards to the way they interfere with cellular mechanisms both in humans and animals (Yamago et al. 1995; Oberdörster et al. 2006; Fujita et al. 2009; Nakagawa et al. 2011). However, much remains to be known about the impact of these carbon molecules on the human body and the environment.

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[2] The name Buckminster fullerene is homage to the American designer, author, and inventor Richard Buckminster "Bucky" Fuller, as C_{60} resembles the geodesic domes that were his trademark

2 The new PV etching process

The "SOLNOWAT" process is an alternative to the current wet chemical etching process used in crystalline PV solar cell production. It has basis in the work on developing dry plasma-based processes (Rentsch et al. 2005; Agostinelli et al. 2005; Lopez et al. 2006; Lopez et al. 2007; Linaschke et al. 2008; Photovoltaics World 2011; Dresler et al. 2012; Piechulla et al. 2011).

The new etching process is however taking place in atmospheric pressure and not in vacuum as has been common in dry plasma etching. It relies on the use of Fluorine (F_2) as the etching gas. This is a very toxic gas, which require that emissions must be avoided. Therefore, a review of regulatory emission control requirements and exposure limits for fluorine and other relevant potential emissions was necessary, in order to implement the necessary precautionary actions in the development of the new etching process.

2.1 Regulatory requirements to the new PV etching process

The work on the compilation of up-to-date European and global emission regulations and requirements are detailed in this paragraph. Some considerations regarding forthcoming regulations are also included.

The compilation took as starting point that the relevant emissions from the new dry etching process for photovoltaic wafers are mainly made up of the four type of fluor-containing gases:

1) Hydrogen fluoride (HF)
2) Fluorine (F_2)
3) Silicon fluorides in general (SiF_x)
4) Silicon tetrafluoride (SiF_4)

In addition, emission regulations for fluoride (F^-) was compiled, as these regulations are relevant in connection with the emission of fluoride-containing compounds escaping the plant in the etching process and potentially contaminating the environment.

Other legal requirements and regulations regarding compounds escaping processing plants and entering the atmosphere are those pertaining to life cycle climate gas emissions and emissions from the scrubbers in the process facilities. Since only wet scrubbers were planned to be applied in the SOLNOWAT process, in theory no gases would be expected to escape from the scrubbers. The regulations pertaining to fluoride (F^-) are thus relevant for scrubber effluents, particularly since hydrogen fluoride gas dissolves in water where it ionizes into F^-.

Other chemical species potentially present in the discharge water from the scrubbers include various breakdown- and reaction products of the reaction between fluorine-containing compounds and water.

Regarding the life cycle climate gas emissions, the two most obvious gases connected to plasma etching of solar cell wafers are nitrogen trifluoride (NF_3) and sulphur hexafluoride (SF_6). These fully fluorinated compounds are commonly used as plasma etch gases and they are extremely potent greenhouse gases. They have 100-year GWPs of 17 200 (NF_3) and 22 800 (SF_6). The Kyoto Protocol and the post-Kyoto process is the regulatory regime for these gases, with the resulting GHG reporting requirements. A key feature of the SOLNOWAT project was that of avoiding the use of these two gases, and developing systems based on gases with zero GWP. The Kyoto Protocol and the post-Kyoto process is in this report dealt with in the last paragraph, on recent and future regulations.

Most of the emission regulations are presented in terms of limit values, which are differing in the various regulations. For air emissions, when only PPM values are stated in the regulations, a conversion into mg/m^3 is made. When the opposite is the case, that values only in mg/m^3 are stated, values are converted into PPM.

2.1.1 Hydrogen fluoride (HF)

HF is a human poison by inhalation (Lewis, 1997). It is a corrosive irritant to skin, eyes and mucous membranes. It also has teratogenic and reproductive effects as well giving skeletal damages. A compilation of air emission regulations for HF has been made by The Norwegian Labour Inspection Authority (Arbeidstilsynet, 2010). This has been supplemented with data from Tylenda (2003) and information from the SOLNOWAT partners. The compilation is shown in Table 2.

Table 2 Air emission regulations for hydrogen fluoride gas (HF) in various countries

Country, organisation/state	**Source**	**Limit value**		**Notation**
		mg/m^3	**ppm**	
European Union	EC (2000)	1.5	1.8	8 hour (8h)
		2.5	3.1	15 min (15m)
Norway	Arbeidstilsynet (2010)	0.5	0.6	Skin uptake (S)[3]

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[3] There are indications that HF is taken up into the body through the skin and can cause swelling and redness. Therefore, a skin uptake notation (S) is implemented in many countries.

		2.0	2.4	Ceiling limit (C)[4], S
Sweden	Arbetsmiljöverket (2005)	1.7	2.1	C
Denmark	Arbejdstilsynet (2007)	1.5	1.8	
Finland	Social- och hälsovårdsministeriet (2007)	1.5	1.8	8h
		2.5	3.1	15m
United Kingdom	Health and Safety Commission (2005)	1.5	1.8	8h
		2.5	3.1	15m
The Netherlands	The Social and Economic Council of the Netherlands (2006)	1	1.2	Time-weighted average (TWA), 15m
USA, National Institute Of Occupational Safety & Health (NIOSH)	American Conference of Governmental Industrial Hygienists (ACGIH) (2009)	2.5	3.1	8h
	NIOSH (2010)	24.5	30	Immediately dangerous to life or health (IDLH)
USA, ACGIH	ACGIH (2009)	0.41	0.5	8h, C
		1.6	2.0	S, Biological exposure index
	ACGIH (2000)	2.5	3.0	C, Short-term exposure limit (STEL)
USA, Occupational Safety & Health Administration (OSHA)	OSHA (2001)	2.0	3.0	Permissible exposure limit (PEL), 8h, TWA, (as F)
USA, Michigan	BNA (2001)	3.0	3.7	PEL, TWA
USA, Montana	BNA (2001)	2.0	2.4	Air contaminant, TWA
USA, New York	BNA (2001)	2.0	2.4	Air contaminant, Threshold limit value (TLV)

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[4] Because there is acute toxicity associated with HF, ceiling limits (C) have been established in many countries.

USA, Washington	BNA (2001)	0.009	0.011	Toxic air pollutant, ASIL
		2.5	3.0	PEL, STEL
Germany, Deutsche Forschungsgemeinschaft (DFG)	DFG (2008)	0.82	1.0	Risk during pregnancy, S
Germany, gov	Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (2007)	0.82	1.0	S
Germany, gov	Gemeinsames Ministerialblatt (2002)	0.0004	0.0005	TWA, 1 year
		0.0003	0.0004	High-sensitivity species and materials
Germany, Verein Deutscher Ingenieure (VDI)	VDI (2011)	0.05	0.06	TWA, 1 year
		0.2	0.24	TWA, 30 min

The EU Scientific Committee on Occupational Exposure Limits (SCOEL) recommends in addition an 8-hour limit value of 2.5 mg/m3 for mixture of HF and inorganic fluorides (SCOEL, 1998).

2.1.2 Fluorine gas (F_2)

F_2 is characterized as a poison gas (Lewis, 1997). It is a very powerful caustic irritant to tissue. It is also a very dangerous fire and explosion hazard.

I the wet scrubber there are several possible reactions between fluorine gas and water, as shown below:

(I) $F_2 (g) + H_2O (l) \rightarrow HOF (g) + HF (g)$ [T = -40°C]

(II) $2 HOF (g) \rightarrow 2 HF (g) + O_2 (g)$ [T = +20°C]

(III) $F_2 (g) + H_2O (l) \rightarrow 2 HF (g) + \frac{1}{2}O_2 (g)$ [T = +20°C] + small amounts of ozone

(IV) $F_2 (g) + 2 H_2O (l) \rightarrow 2 HF (g) + H_2O_2$ [pH<7]

(V) $2 F_2 (g) + 2 OH- \rightarrow 2 F- + OF_2 (g) + H_2O \rightarrow O_2 (g) + 4 F- + 2 H^+$ [pH approx. 14]

Reaction I shows the formation of the chemical compound hypofluorous acid (HOF). HOF is an intermediate in the oxidation of water by F_2 and is decomposing at room temperature to HF and O_2 as shown in reaction II. The hydrogen peroxide (H_2O_2) formed in reaction IV decomposes exothermically in the scrubber effluent to water and oxygen according to the following reaction:

(VI) $2\ H_2O_2 \rightarrow 2\ H_2O\ (l) + O_2\ (g)$

The scrubber must have enough water through-flow to avoid the concentration of hydrogen peroxide to reach levels where explosion might occur. In very alkaline conditions the strongly oxidizing compound oxygen difluoride (OF_2) is formed, as shown in reaction equation V. However, since OF_2 is only an intermediate in this reaction, and decomposes under alkaline conditions to oxygen and fluoride, it is not likely to possess additional emission regulatory challenges than those shown for fluoride later in this report.

A compilation of air emission regulations for F_2 has been made by U.S. Department of Health and Human Services, Public Health Service at Agency for Toxic Substances and Disease Registry (Tylenda, 2003). This is the main basis for the updated compilation shown in Table 3.

Table 3 Air emission regulations for fluorine gas

Country, organisation/state	**Source**	**Limit value**		**Notation**
		mg/m^3	**ppm**	
USA, ACGIH	ACGIH (2000)	1.6	1.0	TLV, TWA
		3.1	2.0	STEL
USA, EPA	EPA (2001)	3.9	2.5	Toxic end point
USA, OSHA	OSHA (2001)	0.2	0.1	PEL, 8h TWA
USA, NIOSH	NIOSH (2010)	0.2	0.1	Recommended exposure limit (REL), TWA
		38.9	25	IDLH
USA, Idaho	BNA (2001)	2	1.3	Occupational exposure limit (OEL)
		0.1	0.06	Acceptable ambient concentration (AAC)
USA, Michigan	BNA (2001)	0.2	0.1	PEL, TWA
USA, Montana	BNA (2001)	0.2	0.1	Air contaminant, TWA
USA, New Mexico	BNA (2001)	2.0	1.3	Toxic air pollutant
USA, New York	BNA (2001)	0.2	0.1	Air contaminant, TLV

USA, Washington	BNA (2001)	0.005	0.003	Toxic air pollutant, ASIL
		0.2	0.1	PEL

2.1.3 Silicon fluorides (SiF_4 and SiF_x)

Silicon tetrafluoride (SiF_4) is the major emission gas, of the four gases HF, SiF_4, SiF_x and F_2, constituting more than 90 % of these emissions. In the air, SiF_4 is formed when hydrogen fluoride reacts with silica. When present in the air SiF_4 is characterised as a poison and is moderately toxic by inhalation (Lewis, 1996). Furthermore, it is a corrosive irritant to skin, eyes and mucous membranes.

In the wet scrubbers the emissions of SiF_4 can react with water in the same manner as it can react with moisture in the air, to form silicon oxide (SiO_2), hydrofluoric acid (Voltaix, 2006) and fluorosilicic acid (H_2SiF_6) (Tylenda, 2003; Lewis, 1997), as shown in the reaction equations below:

(VII) $SiF_4 + 2\ H_2O \rightarrow SiO_2 + 4\ HF$

(VIII) $3\ SiF_4 + 2\ H_2O \rightarrow SiO_2 + 2\ H_2SiF_6$

HF, after its ionizing, contributes to the release of F^- into the environment through the scrubber effluent water. Therefore, the emission regulations for F^- in water (in the next sub-chapter) apply also to SiF_4.

In the USA and Canada H_2SiF_6 is commonly used in drinking water fluoridation and this has spurred a debate on health concerns. This has basis in reports of a relationship between water treated with H_2SiF_6 and elevated levels of lead (Pb) in children's blood (Masters and Coplan, 1999; Masters et al., 2000; Coplan et al., 2007). This association has been attributed to both the effect that incompletely dissociated fluorosilicates in drinking water have on increasing the body's cellular uptake of lead (Pb) (Masters and Coplan, 1999; Masters et al., 2000) and to increased corrosion of Pb-bearing plumbing by fluorosilicates (Coplan et al., 2007). However, the scientific rigour of these studies and the validity of their conclusions have been questioned by Urbansky and Schock (2000). They argue that fluorisilicates are completely hydrolysed before reaching the consumer's tap and therefore has no effect on the solubility and bioavailability of lead.

The safety of using H_2SiF_6 in water fluoridation is however not established. As of 2003, no studies of the chronic effects of H_2SiF_6 use in water fluoridation had been conducted. Safety studies on fluoride have only been conducted using pharmaceutical-grade sodium fluoride, not industrial-grade silicon fluorides (Connett, 2012). Thus it can not be recommended to use wet scrubbers harvested H_2SiF_6 in water fluoridation due to the likelihood of future regulatory barriers.

A third reaction between silicon tetrafluoride and water is shown in the following equation:

(IX) $SiF_4 + 4\ H_2O \rightarrow H_4SiO_4 + 4\ HF$

The orthosilicic acid (H_4SiO_4) that is formed is stable at pH < 3.2. At less acidic conditions it undergoes successive conversion:

(X) $H_4SiO_4 \rightarrow H_{2n+2}Si_nO_{3n+1} \rightarrow (H_2SiO_3)_n \rightarrow (H_6Si_4O_{11})_n \rightarrow (H_2Si_2O_5)_n \rightarrow (SiO_2)_n$

Other silicon fluorides than SiF_4 (here given the abbreviated name SiF_x) can be present in the emissions, however these compounds constitute only minor components of the emission gas mixture of HF, SiF_4, SiF_x and F_2. The silicon fluorides are in this report included in the emission regulations for fluorides in general. Regulations for fluorides in urine of workers exist in the USA, where ACGIH has established BEI-values of 3 and 10 mg/g creatinine prior and end of shift respectively (ACGIH, 2000).

The emission regulations for fluorides in general are shown below in Table 4.

Table 4 Air emission regulations for fluorides in general

Country, organisation/state	**Source**	**Limit value**		**Notation**
		mg/m^3	**ppm**	
USA, ACGIH	ACGIH (2000)	2.5	3.2	
USA, OSHA	OSHA (2001)	2.5	3.2	Fluorides (as F), TLV, TWA
USA, Idaho	BNA (2001)	2.5	3.2	TAP, OEL
		0.125	0.16	TAP, AAC
USA, Michigan	BNA (2001)	2.5	3.2	PEL, TWA
USA, Mississippi	BNA (2001)	3.1	4.0	Groundwater standard (GS)
USA, Montana	BNA (2001)	2.5	3.2	Air contaminant (AC), TWA
USA, New Mexico	BNA (2001)	2.5	3.2	Toxic air pollutant (TAP), OEL
USA, New York	BNA (2001)	2.5	3.2	AC, TLV

USA, Washington	BNA (2001)	0.008	0.010	TAP, ASIL
		2.5	3.2	PEL

2.1.4 Fluoride (F^-)

The emission regulations for fluoride (F^-) are important in connection with emission of fluoride-containing compounds, as the effluent water from the wet scrubbers is likely to contain F^- as a final product from the reaction between these compounds and water.

The compiled set of these regulations are shown in Table 5.

Table 5 Emission regulations for fluoride

Country, organisation/state	**Source**	**Limit value**	**Notation**
		mg/L	
Global, WHO	WHO (2008)	1.5	Drinking water guideline (DWG)
EU	SCHER (2010)	1.5	
USA, Center for Disease Control and Prevention (CDC)	Ozsvath (2009)	0.7-1.2	Drinking water value, depending on average maximum daily temperature
Canada, gov	Ozsvath (2009)	0.8-1.0	Optimal drinking water concentration
India, gov	Ozsvath (2009)	1.0	
China, gov	Ozsvath (2009)	1.0	
USA, Alaska	BNA (2001)	4.0	Maximum contaminant level (MCL)
		2	Secondary MCL (SMCL). Not enforceable, but indicates level at which long-term ingestion of fluoride could cause dental fluorosis.
USA, Arizona	HSBD (2003)	4.0	DWG
	BNA (2001)	2.0	Reporting limit (RL)
USA, California	HSBD (2003)	2.0	Drinking water standards (DWS)

USA, Connecticut	BNA (2001)	4.0	MCL
USA, Delaware	HSBD (2003)	1.8	DWS
USA, Georgia	BNA (2001)	4.0	MCL
USA, Hawai	HSBD (2003)	1.4-2.4	DWS
USA, Idaho	BNA (2001)	4.0	Groundwater quality standard (GQS)
USA, Kansas	BNA (2001)	2.0	Agriculture: Livestock
		1.0	Agriculture: Irrigation
		2.0	Domestic water supply
USA, Maine	HSBD (2003)	2.4	DWG
	BNA (2001)	2.4	Maximum exposure guideline
	BNA (2001)	1.2	Action level
USA, Nebraska	BNA (2001)	4.0	MCL
USA, New Jersey	BNA (2001)	2.0	Groundwater quality criteria
		0.5	PQL
USA, New York	BNA (2001)	3.0	Groundwater effluent limit
		2.2	MCL
USA, North Carolina	HSBD (2003)	4.0	DWS
USA, North Dakota	BNA (2001)	4.0	
USA, Oklahoma	BNA (2001)	4.0	
USA, Pennsylvania	HSBD (2003)	2.0	DWS

The USA Health and Services Department lowered in January 2011 its recommended levels to 0.7 mg F^- per litre due to the danger that some children might get tooth damage from too much fluorine intake (Reuters, 2011).

2.1.5 Recent and future regulations

It is of strong interest for solar cell producers to know what to expect in terms of forthcoming regulations, so that they can adapt their production processes to secure future compliance. Therefore, the work also included an assessment of what can be expected in future regulatory regimes.

Some general prospects of international climate efforts beyond 2012 was presented in the report from the meeting of a selected group of policymakers and stakeholders at Pocantico organised by Pew Center on Global Climate Change, which has been succeded by Center for Climate and Energy Solutions (Pew, 2005). However, the future emission regulations for fluorinated compounds are in part determined by outcomes of the Post-Kyoto Protocol negotiations, due to the high GWP of many of these compounds. These negotiations, which are part of the United Nations Framework Convention on Climate Change (UNFCCC), are attempting to reduce the global emission of GHG emissions.

At the previous UNFCCC meeting in Cancun, Mexico in December 2010, officially referred to as the 16th session of the Conference of the Parties (COP 16), outcomes from the two ad-hoc working groups, on 1) long-term co-operative action and 2) the Kyoto Protocol, formed the so-called Cancun Agreements. These outcomes and the main topics of the Bali Action Plan (established at COP 13 in Bali in 2007) cover:

- a shared vision for long-term cooperative action
- adaptation
- mitigation
- finance
- technology
- capacity building

The results for adaption was one of the topics presented at COP 17, which took place in Durban, South Africa 28 November to 9 December 2011. The primary focus at the Durban conference was however on securing the global climate agreement as the Kyoto Protocol's first commitment period, which covered the period 2008-2012. The future of the Kyoto Protocol was a key issue at his meeting, with the outcome being a second commitment period, with also China willing to take part in the negotiations.

The topics coming out of the Cancun Agreements could potentially have implications for SOLNOWAT, due to the fact that they pertain to "co-operation on clean technology". Thus the topics of the Durban-conference that were most relevant for SOLNOWAT were those connected to mitigation of climate change by reductions in emission of greenhouse gases.

The Subsidiary Body for Scientific and Technological Advice (SBSTA) is responsible for the Methods & Science topic "Scientific, Technical and Socio-Economic Aspects of Mitigation of Climate Change". The thirty-fifth session of SBSTA was organised during COP 17. On the agenda was one specific topic on fluorinated compounds, that can be relevant for SOLNOWAT. The topic of interest was "Implications of the establishment of new hydro-chlorofluorocarbon-22 (HCFC-22) facilities seeking to obtain certified emission reductions for the destruction of hydro-fluorocarbon-23 (HFC-23)" (UNFCCC, 2011a). This is an issue that SBSTA considers in collaboration with the clean development mechanism (CDM) (UNFCCC, 2011b). The outcome could have implications for technology based on the SOLNOWAT etching process, through potential certified emission reductions from the establishing of future dry PV production facilities, due to the avoidance of NF_3 and SF_6 emissions, possibly as a part of CDM.

2.2 Life Cycle Assessment

2.2.1 Purpose

The purpose of the LCA was to compare the environmental impacts from the wet (current) and dry (SOLNOWAT) PV etching processes. Through the comparison, advantages and/or disadvantages associated with both processes was elucidated. The LCA determined environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal.

2.2.2 Methods

LCA is both theoretically and methodologically defined by the International Standards Organisation through the 14040 Environmental management – life-cycle assessment – principles and framework (ISO, 2006) . Generally stated, LCA addresses the environmental aspects of the product system. The product system consists of raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. The methodolocial steps are outlined in the following subsections, and their interrelation is depicted in Figure 1.

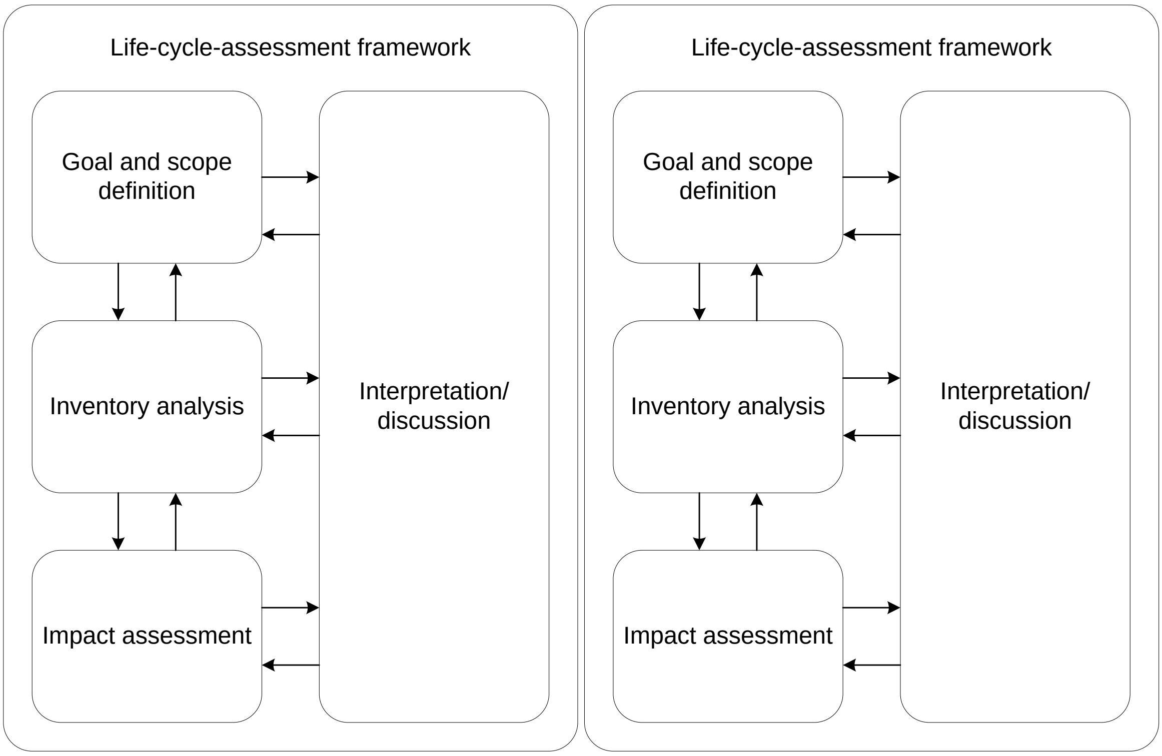

Figure 1 Methodolocial framework of life-cycle assessment according to ISO 14040 series

2.2.3 Goal and Scope Definition

In the goal and scope definition, which is the first phase of the LCA, clarifies the aim of the study, the functional unit, the system alternatives considered, and the breadth and depth of the LCA in relation to this aim.

In the first step of the goal and scope definition the goal of the LCA study was stated and justified, explaining the goal (aim or objective) of the study and specifying the intended use of the results (application), the initiator (commissioner) of the study, the practitioner, the stakeholders and for whom the target audience. The following bullets give answer to those requirements stated by ISO (2006), and have been formulated in conjunction with the Solnowat project partners, and from Annex 1 – 'Description of Work' for Solnowat (2011).

Goal:

- The intended application:
    1. Compare the operation texturing phase environmental impact of the dry- and conventional wet- PV solar wafer etching processes, with particular focus on: global warming potential and water consumption.
- The reasons for carrying out the study:
    2. To aid in develop a dry route alternative for the solar cell industry that will eliminate the very high water consumption and GWP emissions of current process
- The intended audience

    3. Solnowat project partners
- Level of disclosure
    4. Internal document

In following the CML guide (2001), it is in the scope definition step that the main characteristics of an intended LCA study are established, covering such issues as temporal, geographical and technology coverage, the mode of analysis employed and the overall level of sophistication of the study. The following bullets give answer to those requirements stated by ISO (2006), and have been formulated in conjunction with the Solnowat project partners, as well as from Annex 1 – 'Description of Work' for Solnowat (2011).

Scope

- The product system to be studied
    - Specified in the document: Solnowat - Annex 1 'description of work'
- The function of the product system(s)
    - PV solar wafer etching
- The functional unit
    - One PV solar cell wafer
- The system boundary
    - Figure 2 depicts the system boundary for the dry-etch process. Corresponding system boundaries have been adoped for the wet-etching process (based on information from Jochen Rentsch of Fraunhofer ISI).

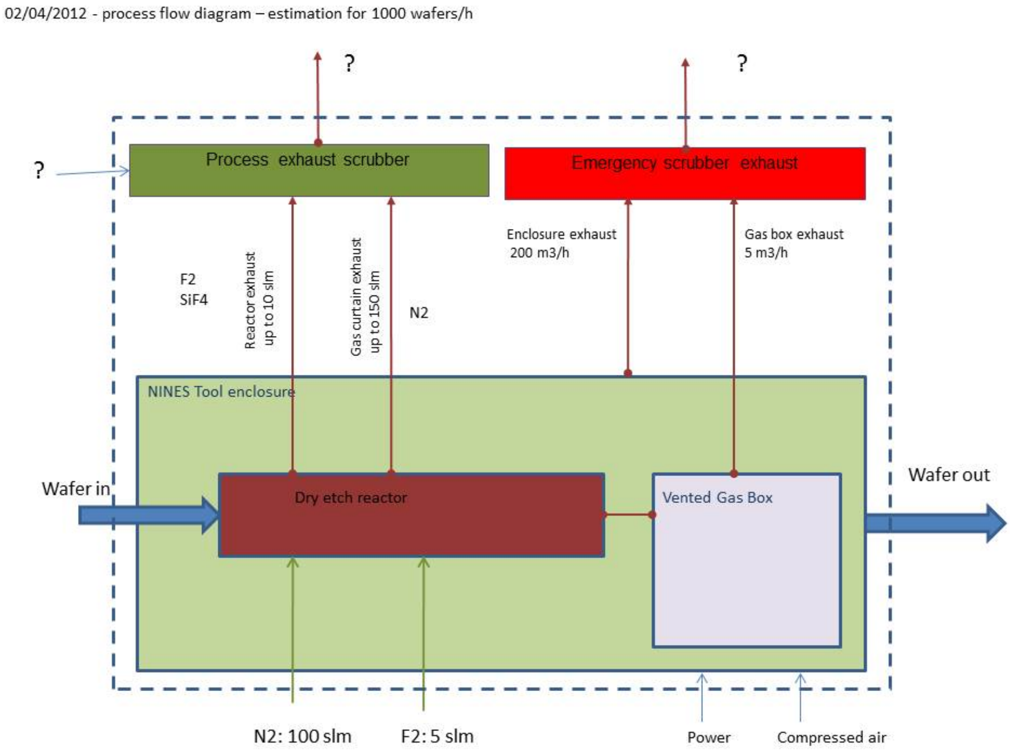
02/04/2012 - process flow diagram – estimation for 1000 wafers/h

Figure 2 Process flow diagram of the SOLNOWAT dry-etch process

- Allocation procedures
    - No first order (direct) allocation used. For information concerning second order (indirect) allocation please refer to the life-cycle inventories applied from the Simapro/Ecoinvent database.
- Impact categories selected and methodology of impact assessment, and subsequent interpretation to be used:
    - CML 2 Baseline impact categories and impact assessment methods, along with inventory results for water consumption.
- Data requirements
    - N/A
- Assumptions
    - N/A
- Limitations
    - This environmental assessment is only for the operation texturing phase and is based on a several preliminary documents, and as such one should be careful to base claims solely on these results.
- Initial data quality requirements
    - N/A
- Type of critical review, if any:
    - None applied

- Type and format of the report required
    - Internal report

2.2.4 Life-cycle inventory

According to the CML guide (2001), in the goal and scope definition phase the basic groundplan for the study was established. The second phase of the LCA is the inventory analysis. This phase was concerned with the collection of the data necessary to meet the goals of the defined study and with the associated data collection and calculation procedures, and was essentially an inventory of input/output data with respect to the system being studies.

The process inventory was based on internal project documents provided by the SOLNOWAT coordinator NINES Photovoltaics:

- Nines Dry Etch Cost of Ownership Review v0.1, and
- Operation_Cost_Calculation_Facilities 05102011 Ed(2).xls

Both received from E. Duffy 24.04.2012. Along with updated information concerning the wet, and dry processes:

- Solnowat_Texturing_ConsumptionWetChemicals_130704.xlsx
- Solnowat_Texturing_Consumption Dry Chemicals.xlsx

Received from: E. Duffy 26.09.2013, and J. Rentsch 04.07.2013 respectively.

The data was conditioned to the functional unit ‘per wafer’, detailes in the life-cycle inventories in Appendix I.

2.2.5 Results

Life-cycle impact assessment

Figure 3 presents the life-cycle impact assessment results for all 4 texturing proceses, without uncertainty as determined by the CML 2 baseline mid-point impact assessment method.

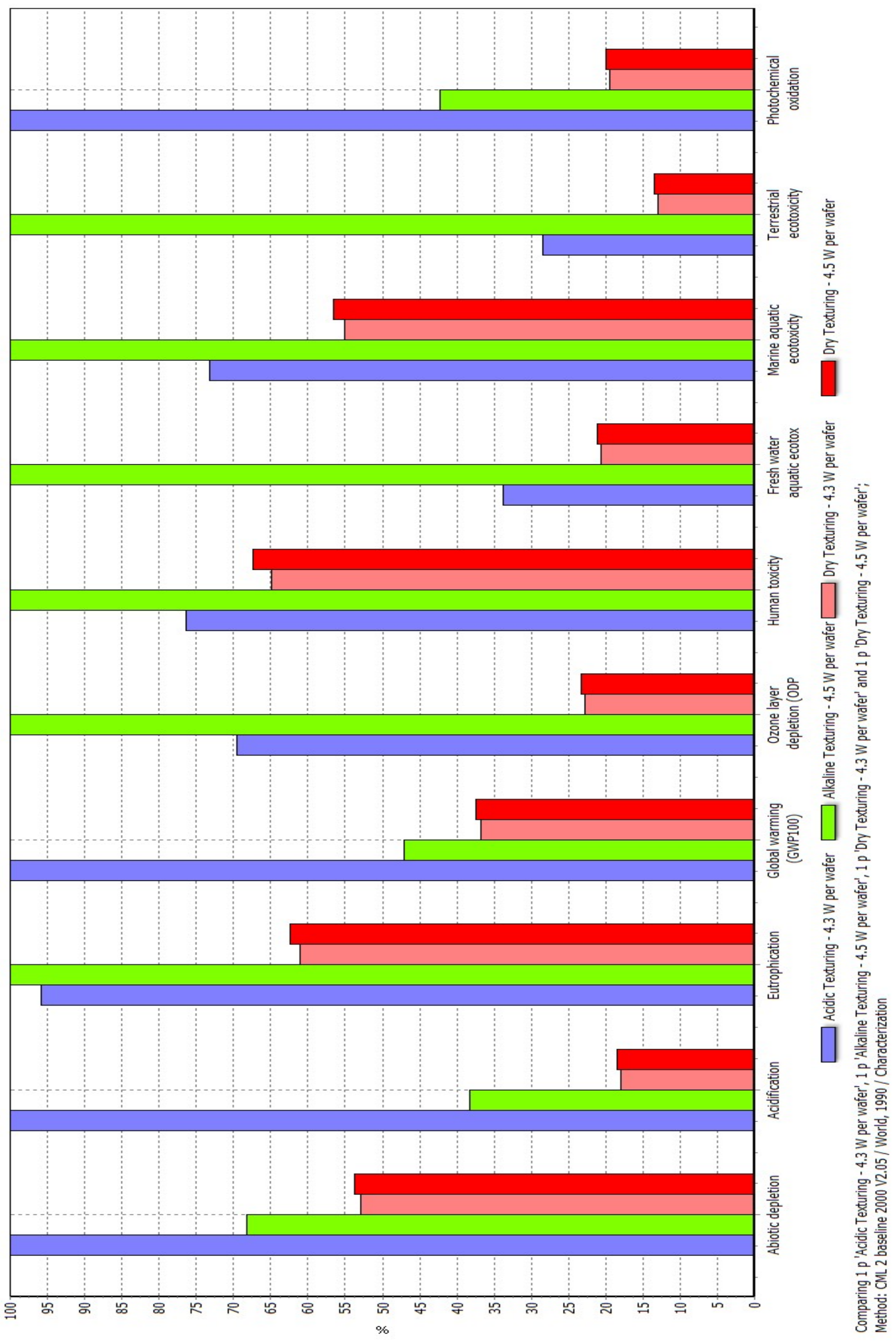

Figure 3 Life-cycle impact assessment results

From the results presented in Figure 3 we see that the dry texturing processes provide reductions for all impact categories with respect to their corresponding wet texturing process.

However, as included in Appendix IV we can see that several of the impact categories have been determined with great uncertainty.

In the following graphs we have collected two relevant impact categories for comparison: GWP and toxicity. We have judged it appropriate to include a closer review of toxicity in this report. Total toxicity as presented includes the values from 4 separate impact categories: human toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, and terrestrial eco-toxicity measured in kg. 1.4 DB eq. The results are shown in Figure 4 and Figure 5.

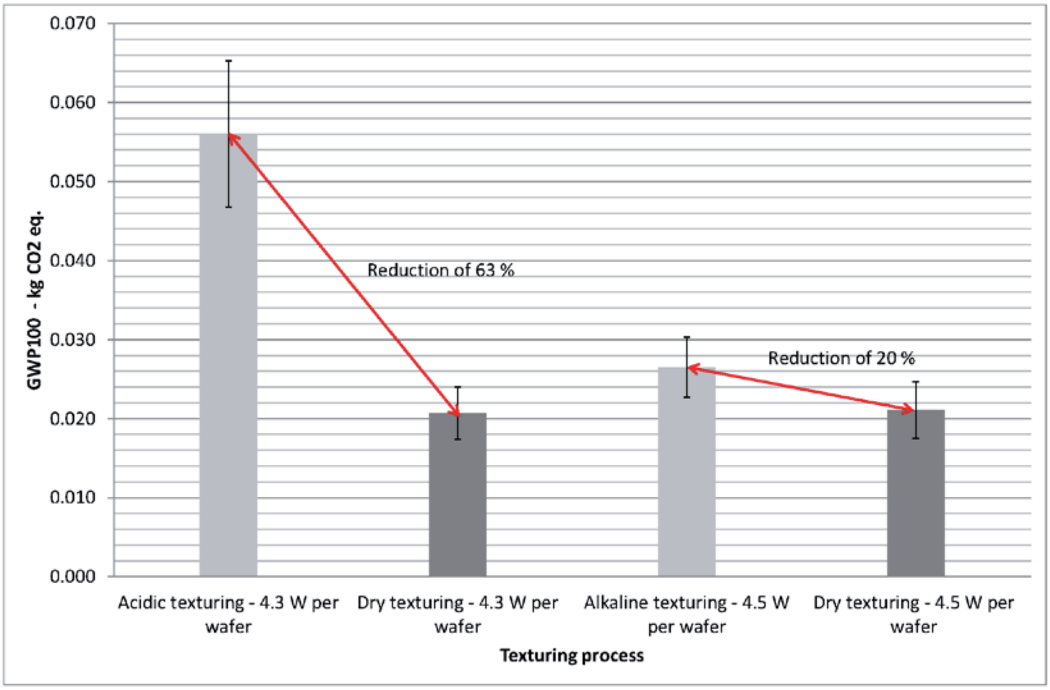

Figure 4 Life-cycle impact assessment results for GWP100 for all 4 texturing processes, including data uncertainty

From Figure 4, based on data given in section Appendix IV, it can be observed that the dry texturing processes have led to reductions of 63 % and 20 % with respect to their corresponding wet texturing processes, i.e. 4.3 W per wafer, and 4.5 W per wafer respectively. Additionally the uncertainty determined is within an acceptable range.

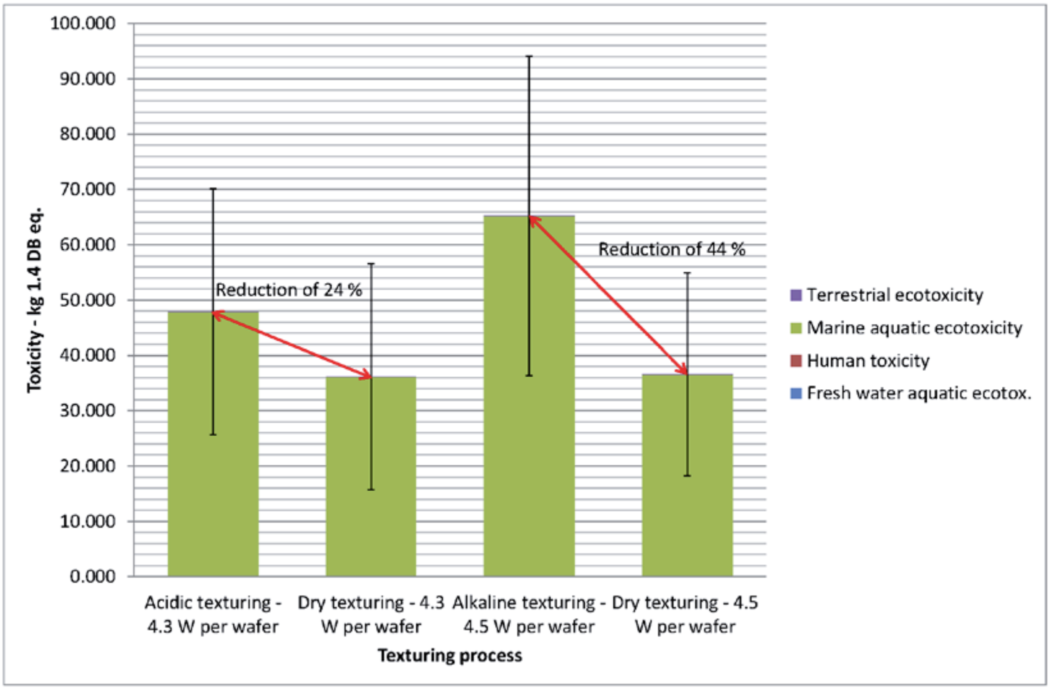

Figure 5 Life-cycle impact assessment for total toxicity for all 4 texturing processes, including data uncertainty

From Figure 5, based on data given in Appendix IV, it can be observed that the dry texturing processes have led to reductions of 24 % and 44 % with respect to their corresponding wet texturing processes, i.e. 4.3 W per wafer, and 4.5 W per wafer respectively. The uncertainty determined is however high. In Appendix IV it can be seen that marine aquatic eco-toxicity is the predominant contributor for all texturing processes. This indicates that the final fate of toxic emissions is predominantly in the marine environment.

Water consumption (direct and indirect)

Water consumption does not constitute an impact category in the CML 2 baseline mid-point impact assessment method. As such, total water consumption was determined by investigating the inventory results; including both the direct and indirect consumption of water. Water for cooling and water passing through turbines for the generation of electricity were not included in this determination, as it is assumed that this water leaves the system under study unchanged. The following four figures present the results for the texturing processes For the source data please refer to Appendix IV Water consumption tables of results.

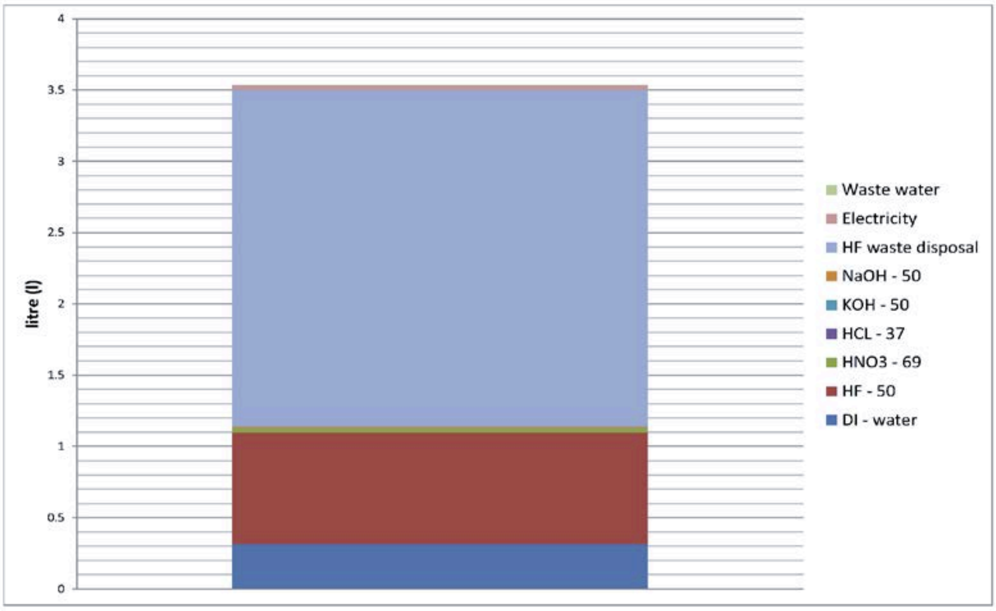

Figure 6 Total water consumption of the acidic texturing process of a 4.3 W wafer

In Figure 6 we observe that the use of: hydrogen fluoride (HF) in waste disposal, HF-50 (50%wt solution), and deionised water are the strongest contributors to water consumption in the acidic texturing process of a 4.3 W wafer, contributing: 67 vol. %, 22 vol. %, and 9 vol. % of the total consumption respectively. It can be interpreted that indirectly, the production of HF consumes great volumes of water, and as such any reduction in HF consumption would lead to overall reductions in water consumption, in addition to any reductions in the direct use of deionised water.

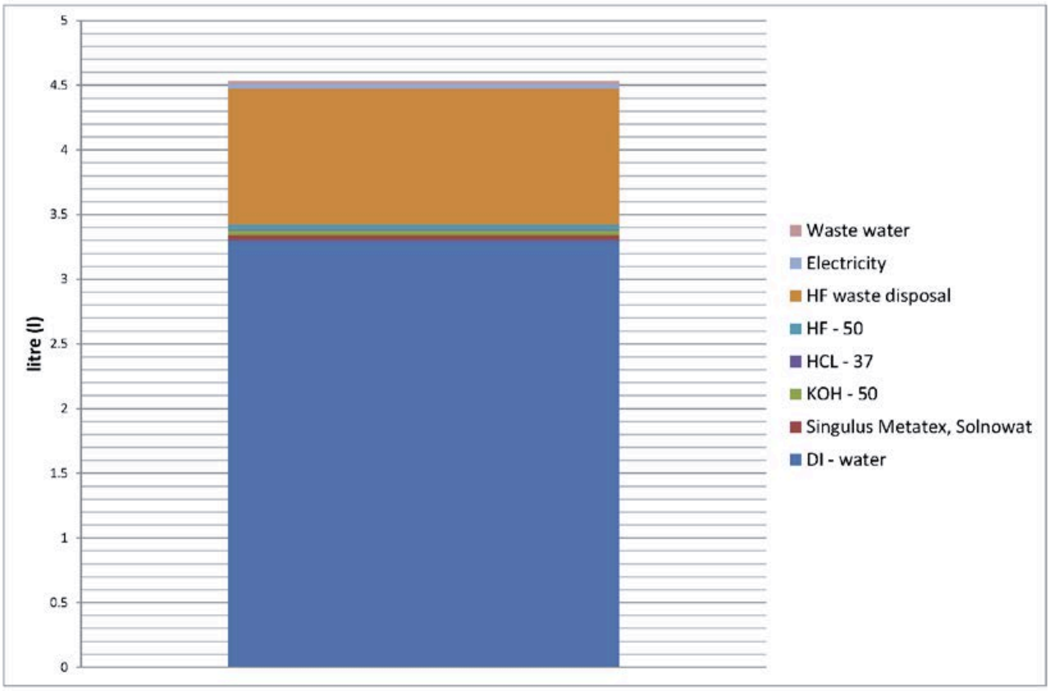

Figure 7 Total water consumption of the alkaline texturing process of a 4.5 W wafer

In Figure 7 we observe that the use of: deionised water and hydrogen fluoride (HF) in waste disposal are the strongest contributors to water consumption in the alkaline texturing process of a 4.5 W wafer, contributing: 73 vol. % and 23 vol. % of the total consumption respectively. It can be interpreted that indirectly, the production of HF consumes large volumes of water, and as such any reduction in HF consumption would lead to overall reductions in water consumption, in addition to any reductions in the direct use of deionised water.

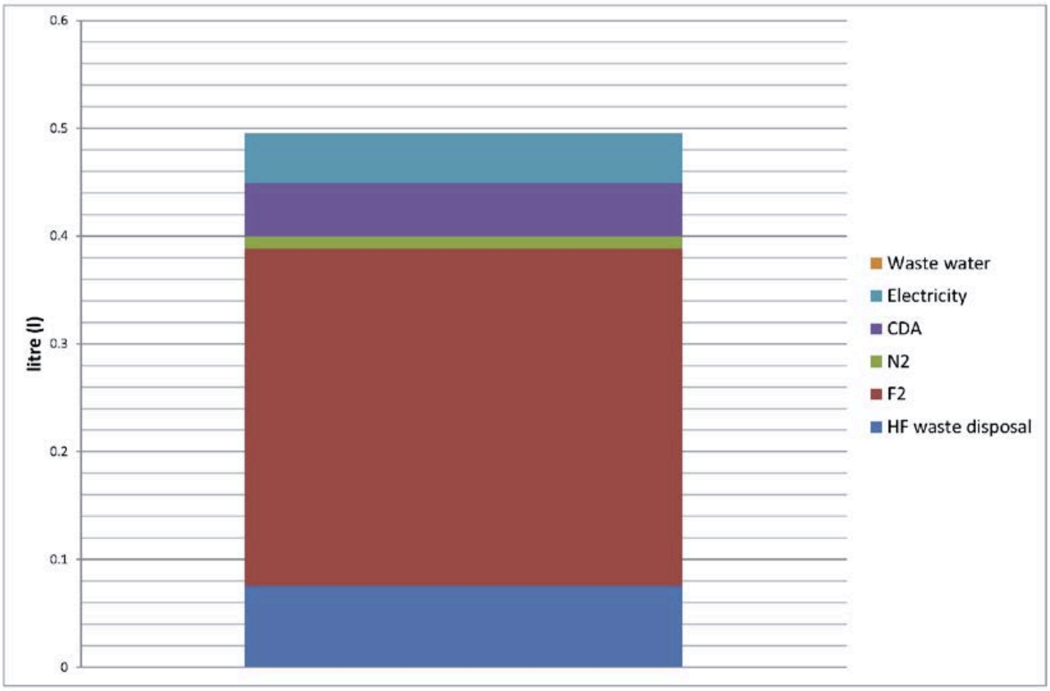

Figure 8 Total water consumption of the dry texturing process of a 4.3 W wafer

In Figure 8 we san see that the use of: fluorine gas and hydrogen fluoride (HF) in waste disposal are the strongest contributors to water consumption in the dry texturing process of a 4.3 W wafer, contributing: 63 vol. % and 15 vol. % of the total consumption respectively. It can be interpreted that indirectly, the production of fluorine gas consumes large volumes of water, and as such any reduction in flourine consumption would lead to overall reductions in water consumption.

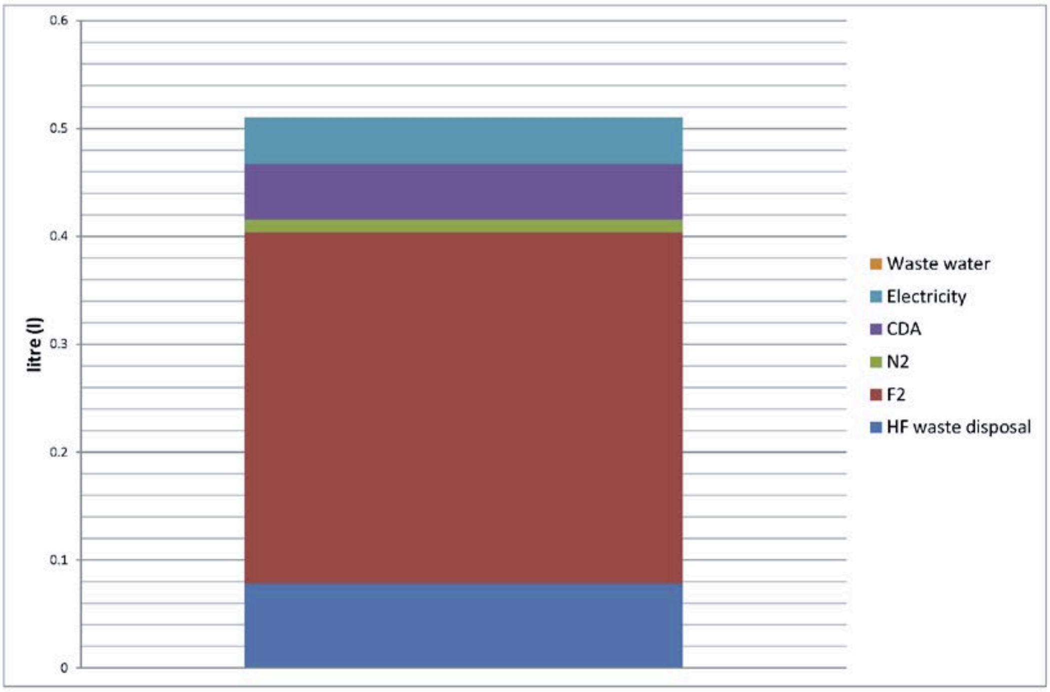

Figure 9 Total water consumption of the dry texturing process of a 4.5 W wafer

In Figure 9 we observe that the use of: fluorine gas and hydrogen fluoride (HF) in waste disposal are the strongest contributors to water consumption in the dry texturing process of a 4.5 W wafer, contributing: 64 vol. % and 15 vol. % of the total consumption respectively. Indirectly, the production of fluorine gas consumes large volumes of water, so reductions in flourine consumption would lead to overall reductions in water consumption.

The collected results for water consumption are presented in Figure 10.

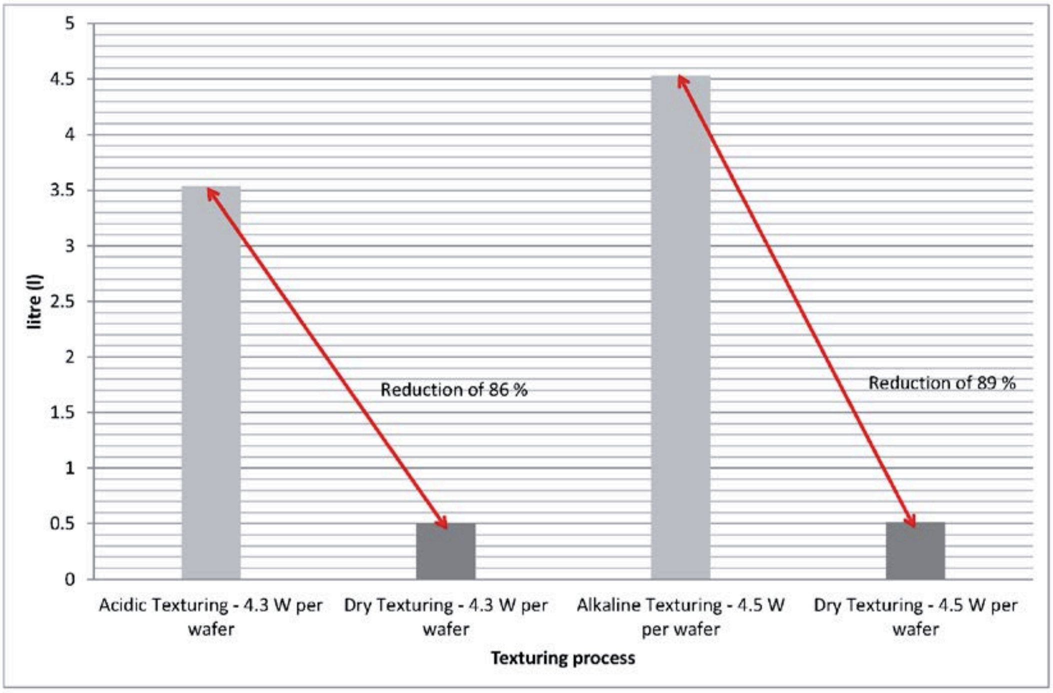

Figure 10 Collected water consumption results for all four texturing processes

In Figure 10 it is shown that with respect to watts per wafer, the dry texturing process leads to reductions of 86 vol. % and 89 vol. % for 4.3 W and 4.5 W per wafer respectively.

3 Interpretation of results

The interprestation of the results is conducted in Appendix I-IX.

4 Conclusions

The life cycle assessment of the dry etching (“Solnowat”) process in comparison with state of the art wet chemical etching for photovoltaic wafers has revealed that the Solnowat etching has significantly lower GHG emissions (GWP) and water consumption. This is foundto be true also after extensive uncertainty analysis.

The dry texturing process implies GWP reductions of 63 % and 20 % with respect to their corresponding wet texturing processes, i.e. 4.3 W per wafer, and 4.5 W per wafer respectively.

The dry texturing process leads to water reductions of 85 vol. % and 89 vol. % for 4.3 W and 4.5 W per wafer respectively. Thus the dry process is better in terms of both lower GWP and lower water consumption.

Though the uncertainty determined is high, the dry texturing processes imply toxicity reductions of 24 % and 44 % with respect to their corresponding wet texturing processes, i.e. 4.3 W per wafer, and 4.5 W per wafer respectively. It can be seen that marine aquatic ecotoxicity is the predominant contributor for all texturing processes. This implies that the final fate of toxic emissions is predominantly in the marine environment.

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Appendix 1 – Life-cycle inventories

As mentioned in Section **Feil! Fant ikke referansekilden.** Life-cycle inventory, the source for the inventories are primarily the two documents:

- Solnowat_Texturing_ConsumptionWetChemicals_130704.xlsx, provided by E. Duffy 26.09.2013
- Solnowat_Texturing_Consumption Dry Chemicals.xlsx, provided by J. Rentsch 04.07.2013

The original data was been conditioned based on commonly accepted values for density. Due to the absence of exact data for Sigulus Metatex (Singulus Technologies, 2012), the authors have assumed a mass ratio of: 4:48:48 for potassium hydroxide, Isoproturon (isopropyl alcohol), and deionized water respectively.

Appendix Table 1 Life-cycle inventory for the acidic texturing process for one 4.3 W wafer

Products		
Acidic Texturing - 4.3 W per wafer	1	p
Materials/fuels		
Water, deionised, at plant/CH U	0,25071	kg
HF - 50, Solnowat	0,00535	kg
Nitric acid, 50% in H2O, at plant/RER U	0,00717	kg
Hydrochloric acid, 36% in H2O, from reacting propylene and chlorine, at plant/RER U	0,00092	kg
KOH - 50, Solnowat	0,00015	kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	0,00064	kg
Hydrogen fluoride, at plant/GLO U	0,00812	kg
Electricity/heat		
Electricity, production mix RER/RER U	0,007	kWh
Waste to treatment		
Treatment, wafer fabrication effluent, to wastewater treatment, class 2/CH U	0,30642	l

Appendix Table 2 Life-cycle inventory for the alkaline texturing process for one 4.5 W wafer

Products		
Alkaline Texturing - 4.5 W per wafer	1	p
Materials/fuels		
Water, deionised, at plant/CH U	2,61074	kg
Singulus MetaTEX200, Solnowat	0,0014	kg
KOH - 50, Solnowat	0,00439	kg
H2O2 - 30, Solnowat	0,00199	kg
Hydrochloric acid, 36% in H2O, from reacting propylene and chlorine, at plant/RER U	0,00443	kg
HF - 50, Solnowat	0,00029	kg
Hydrogen fluoride, at plant/GLO U	0,00362	kg

Electricity/heat		
Electricity, production mix RER/RER U	0,0071	kWh
Waste to treatment		
Treatment, wafer fabrication effluent, to wastewater treatment, class 2/CH U	2,61767	l

Appendix Table 3 Life-cycle inventory for the dry texturing process for one 4.3 W wafer

Products		
Dry Texturing - 4.3 W per wafer	1	p
Materials/fuels		
Hydrogen fluoride, at plant/GLO U	0,00026	kg
Fluorine, liquid, at plant/RER U	0,00077	kg
Nitrogen, liquid, at plant/RER U	0,00283	kg
Compressed air, optimised generation, <30kW, 10 bar gauge, at compressor/RER U	27,12096	l
Electricity/heat		
Electricity, production mix RER/RER U	0,01047	kWh
Waste to treatment		
Treatment, wafer fabrication effluent, to wastewater treatment, class 2/CH U	0,02363	l

Appendix Table 4 Life-cycle inventory for the dry texturing process for one 4.5 W wafer

Products		
Dry Texturing - 4.5 W per wafer	1	p
Materials/fuels		
Hydrogen fluoride, at plant/GLO U	0,00027	kg
Fluorine, liquid, at plant/RER U	0,0008	kg
Nitrogen, liquid, at plant/RER U	0,00296	kg
Compressed air, optimised generation, <30kW, 10 bar gauge, at compressor/RER U	28,3824	l
Electricity/heat		
Electricity, production mix RER/RER U	0,00974	kWh
Waste to treatment		
Treatment, wafer fabrication effluent, to wastewater treatment, class 2/CH U	0,024732	l

Appendix Table 5 Life-cycle inventory for the production of 1 kg of 50 wt. % hydrogen fluoride in deionised water

Products		
HF - 50, Solnowat	1	kg
Materials/fuels		
Hydrogen fluoride, at plant/GLO U	0,5	kg
Water, deionised, at plant/CH U	0,5	kg

Appendix Table 6 Life-cycle inventory for the production of 1 kg of 50 wt. % potassium hydroxide in deionised water

Products		
KOH - 50, Solnowat	1	kg
Materials/fuels		
Water, deionised, at plant/CH U	0,5	kg
Potassium hydroxide, at regional storage/RER U	0,5	kg

Appendix Table 7 Life-cycle inventory for the production of Singulus MetaTEX200, based on: Singulus Technologies (2012), and discussion with J. Rentsch of Fraunhofer ISI

Products		
Singulus MetaTEX200, Solnowat	1	kg
Materials/fuels		
Potassium hydroxide, at regional storage/RER U	0,04	kg
Isoproturon, at regional storage/RER U	0,48	kg
Water, deionised, at plant/CH U	0,48	kg

Appendix Table 8 Life-cycle inventory for the production of 1 kg of 30 wt. % hydrogen peroxide in deionised water

Products		
H2O2 - 30, Solnowat	1	kg
Materials/fuels		
Hydrogen peroxide, 50% in H2O, at plant/RER U	0	kg
Water, deionised, at plant/CH U	0	kg

Appendix II – Results – Life-Cycle Impact Assessment (LCIA)

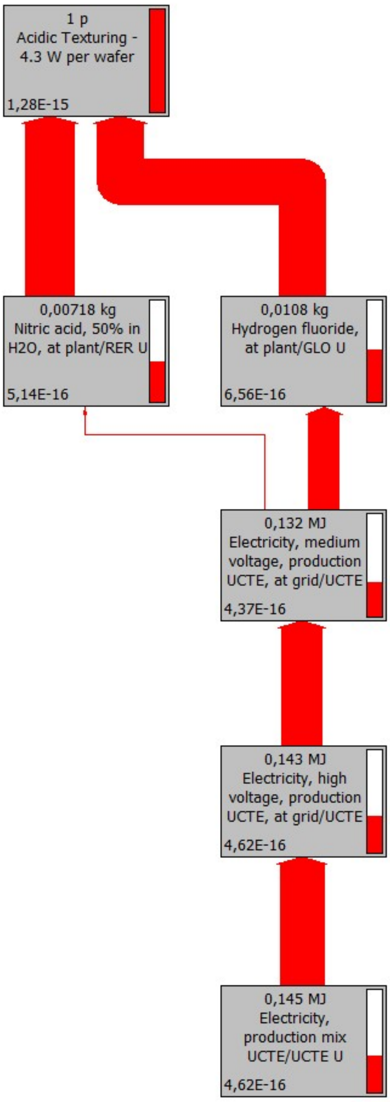
The following table presents the complete results of the life-cycle impact assessment, i.e. all 10 impact categories as determined using CML 2 baseline mid-point impact assessment method. Data uncertainty is not given.

Appendix Table 9 Life-cycle impact assessment results for all 4 etching process without data uncertainty

Impact category	**Unit**	**Acidic Texturing - 4.3 W per wafer**	**Alkaline Texturing - 4.5 W per wafer**	**Dry Texturing - 4.3 W per wafer**	**Dry Texturing - 4.5 W per wafer**
Abiotic depletion	kg Sb eq	0,00028642	0,0001956	0,00015168	0,00015381
Acidification	kg SO2 eq	0,00113495	0,00043462	0,00020355	0,00020929
Eutrophication	kg PO4--- eq	0,00012175	0,00012708	7,7559E-05	7,9227E-05
Global warming (GWP100)	kg CO2 eq	0,05619201	0,02644041	0,02070099	0,02100101
Ozone layer depletion (ODP)	kg CFC-11 eq	3,2238E-09	4,6352E-09	1,0563E-09	1,0765E-09
Human toxicity	kg 1,4-DB eq	0,04183078	0,05474828	0,03554363	0,03688928
Fresh water aquatic ecotox.	kg 1,4-DB eq	0,02718134	0,08060555	0,0165916	0,01704551
Marine aquatic ecotoxicity	kg 1,4-DB eq	47,1792864	64,4114545	35,4345057	36,3955077
Terrestrial ecotoxicity	kg 1,4-DB eq	0,0004083	0,00143576	0,00018614	0,00019315
Photochemical oxidation	kg C2H4 eq	4,3536E-05	1,8435E-05	8,4599E-06	8,7057E-06

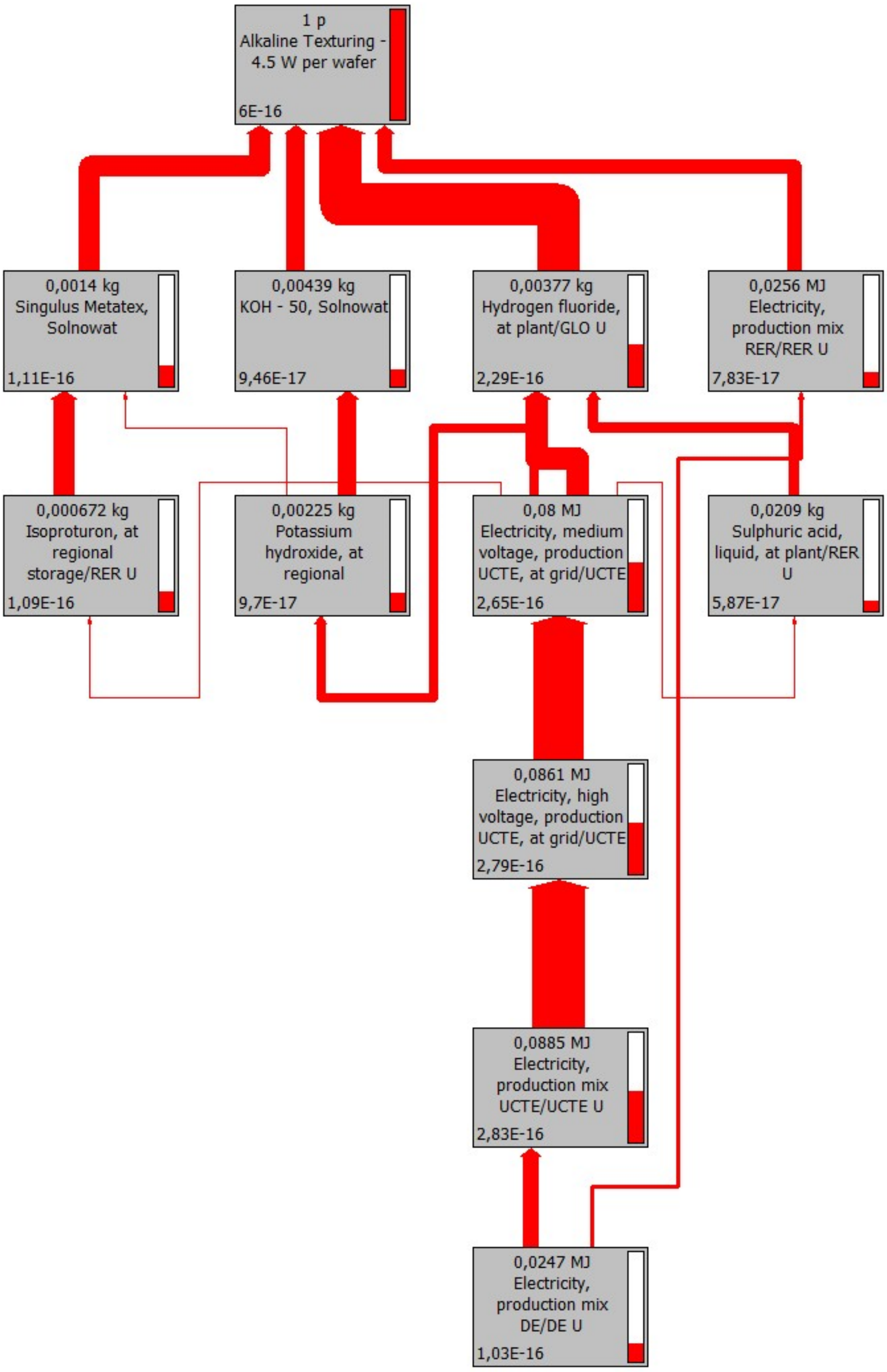
Appendix III – Results – Contribution Analysis for Global Warming Potential

Contribution analysis reveals which processes are playing a significant role in the results. It is intended that with this information one can focus attention on these processes, and analyse if these processes are sufficiently representative, complete and if there are important assumptions within these processes. Here, contribution analysis is presented by a graphical representation of the process tree or network. In the process tree, a small thermometer indicates the relative contribution of the process. The advantage of this approach is that one can exactly see what the role of the process in the life- cycle is, adapted from Goedkoop et al. (2010).



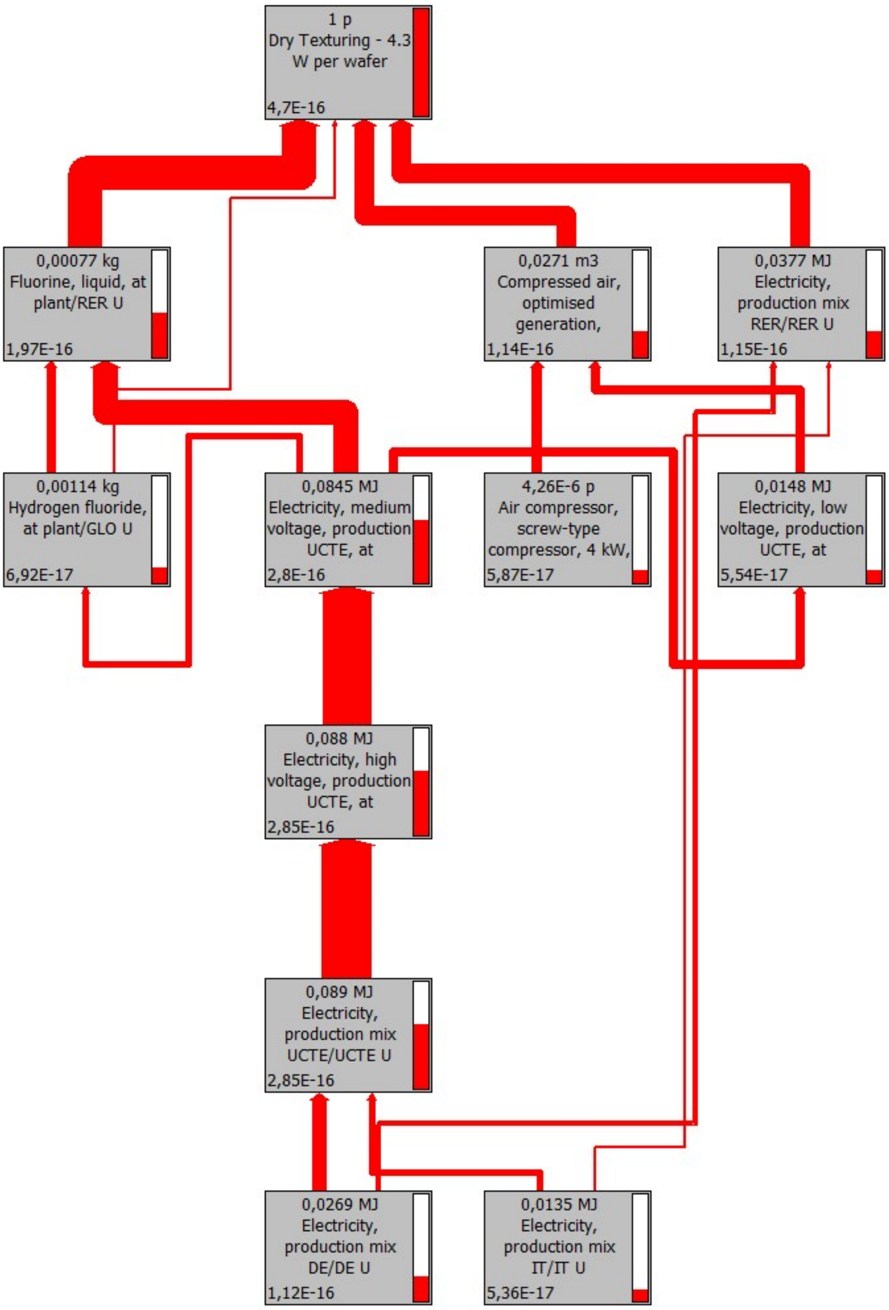
Appendix Figure 1 Contribution analysis tree for GWP – acidic texturing of one 4.3 W wafer

As can be seen in this contribution analysis tree, the greatest contributors to GWP in the acidic texturing process are: the production of nitric acid, and hydrogen fluoride. Also revealed is that the provision of electricity contributes greatly to the GWP effect of hydrogen fluoride. As such, it can be interpreted that reductions in these two consumables, and careful selection of hydrogen fluoride whose production is based electricity with lower environmental effect would lead to an overall reduction in determined GWP.



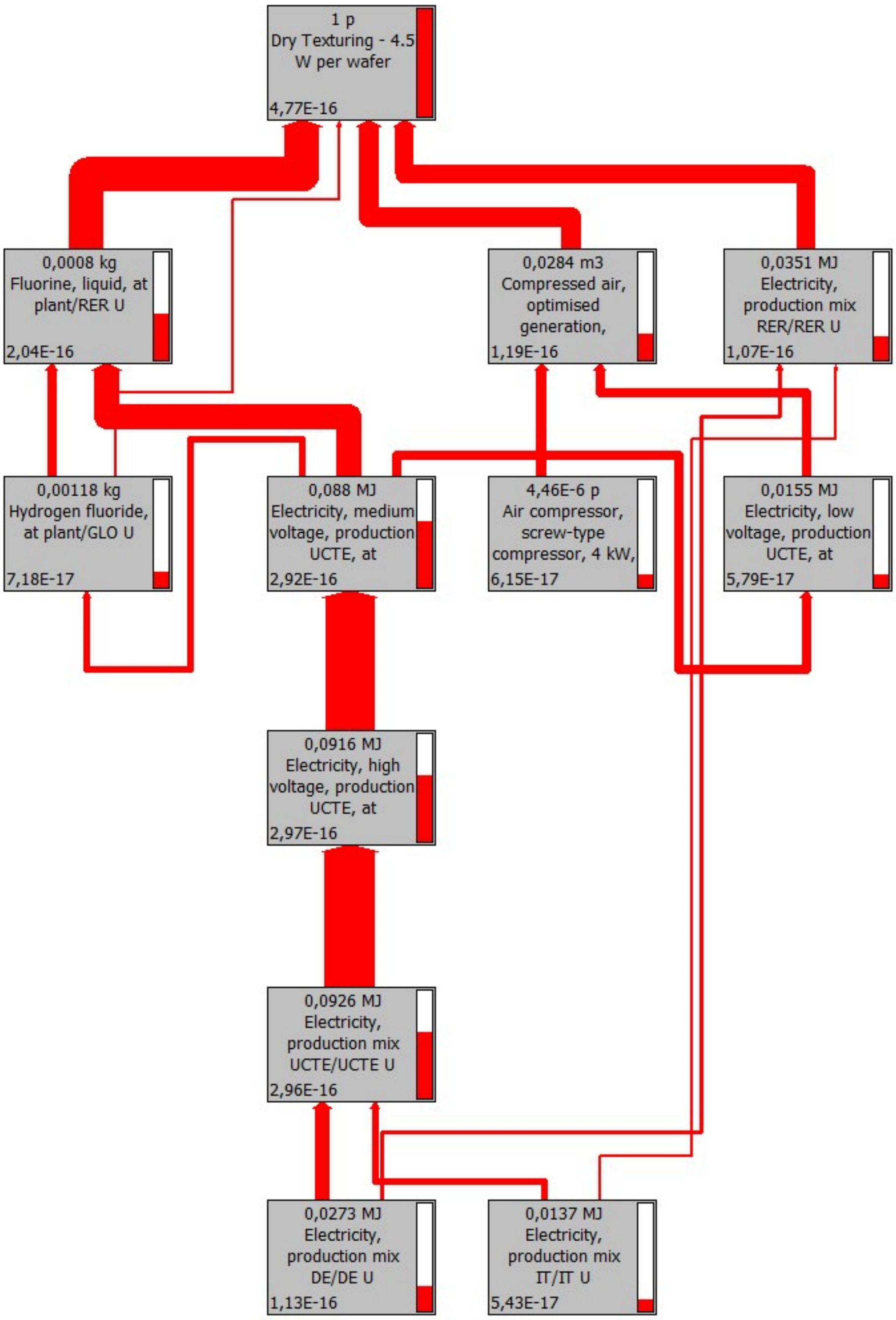
Appendix Figure 2 Contribution analysis tree for GWP – alkaline texturing of one 4.5 W wafer

As can be seen in this contribution analysis tree, the greatest contributors to GWP in the alkaline texturing process are: the production of Singulus MetaTEX200, potassium hydroxide, hydrogen fluoride, and the provision of electricity based on European production mix averages. Due to the uncertainty in the inventory of Singulus MetaTEX200, see Appendix 1, one should be hesitant to base decisions this this particular result. It can though be interpreted that reductions in the remaining consumables, and particularly the careful selection of hydrogen fluoride whose production is based electricity with lower environmental effect would lead to an overall reduction in determined GWP.



Appendix Figure 3 Contribution analysis tree for GWP – dry texturing of one 4.3 W wafer

As can be seen in this contribution analysis tree, the greatest contributors to GWP in this dry texturing process are: the production of fluorine and the provision of compressed air and electricity based on European production mix averages. Considering that both fluorine production and compressed air consume large amounts of electricity, it can though be interpreted that reductions in electricity consumption, and/or the careful selection of electricity with lower environmental effect would lead to an overall reduction in determined GWP.



Appendix Figure 4 Contribution analysis tree for GWP – dry texturing of one 4.5 W wafer

Similar to the previous contribution analysis tree, the greatest contributors to GWP in this dry texturing process are: the production of fluorine and the provision of compressed air and electricity based on European production mix averages. Considering that both fluorine production and compressed air consume large amounts of electricity. Similarly it can be interpreted that reductions in electricity consumption, and/or the careful selection of electricity with lower environmental effect would lead to an overall reduction in determined GWP.

Appendix IV – Results – Uncertainty Analysis

Data uncertainty (standard deviation) with a 95 % confidence interval has been determined using Monte Carlo analysis with 1000 runs. Initial square geometric standard deviation has been determined using the pedigree matrix method developed by Weidema and Wesnaes (1996) included in the Ecoinvent database (Simapro 7) software. The square geometric standard deviation is 1.4 for all flows excluding Singulus MetaTEX200 which is 1.68, all with a logarithmic distribution.

Appendix Table 10 Uncertainty analysis, and impact assessment, of the acidic texturing of one 4.3 W wafer

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2,5%	97,5%	Std.err.of mean
Abiotic depletion	kg Sb eq	0,000287	0,00028	0,0000572	19,9%	0,000203	0,000421	0,0063
Acidification	kg SO_2 eq	0,00107	0,000876	0,000803	75,4%	0,000561	0,00289	0,0238
Eutrophication	kg PO_4--- eq	0,000126	0,00011	0,000062	49,1%	0,000059	0,000297	0,0155
Fresh water aquatic ecotox.	kg 1,4-DB eq	0,0276	0,025	0,0117	42,3%	0,0145	0,053	0,0134
Global warming (GWP100)	kg CO_2 eq	0,056	0,055	0,00925	16,5%	0,0408	0,0764	0,00522
Human toxicity	kg 1,4-DB eq	0,042	0,0368	0,0212	50,5%	0,0204	0,0964	0,016
Marine aquatic ecotoxicity	kg 1,4-DB eq	47,8	42,3	22,2	46,5%	23,2	113	0,0147
Ozone layer depletion (ODP)	kg CFC-11 eq	3,2E-09	3,04E-09	8,18E-10	25,6%	2E-09	5,37E-09	0,00809
Photochemical oxidation	kg C_2H_4 eq	0,0000408	0,0000331	0,0000321	78,8%	0,0000206	0,000114	0,0249
Terrestrial ecotoxicity	kg 1,4-DB eq	0,000407	0,000383	0,000122	30,1%	0,000232	0,000716	0,00951
Confidence interval:	95							

Appendix Table 11 Uncertainty analysis, and impact assessment of the alkaline texturing of one 4.5 W wafer.

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2,5%	97,5%	Std.err.of mean
Abiotic depletion	kg Sb eq	0,000196	0,000192	0,0000302	15,4%	0,000146	0,000265	0,00487
Acidification	kg SO_2 eq	0,000445	0,000349	0,000371	83,4%	0,000227	0,00126	0,0264
Eutrophication	kg PO_4--- eq	0,000127	0,00012	0,0000356	28,1%	0,0000786	0,000218	0,00888
Fresh water aquatic ecotox.	kg 1,4-DB eq	0,082	0,0732	0,041	49,9%	0,0348	0,178	0,0158
Global warming (GWP100)	kg CO_2 eq	0,0265	0,0262	0,00381	14,4%	0,0201	0,0349	0,00455
Human toxicity	kg 1,4-DB eq	0,0544	0,0517	0,0158	29%	0,0324	0,0931	0,00917
Marine aquatic ecotoxicity	kg 1,4-DB eq	65,1	58,5	28,8	44,2%	32	129	0,014
Ozone layer depletion (ODP)	kg CFC-11 eq	4,63E-09	4,44E-09	1,11E-09	24%	3,04E-09	7,14E-09	0,00758
Photochemical oxidation	kg C_2H_4 eq	0,0000189	0,0000151	0,0000149	78,9%	0,00000982	0,0000513	0,0249
Terrestrial ecotoxicity	kg 1,4-DB eq	0,00142	0,00123	0,000796	56%	0,000508	0,00358	0,0177
Confidence interval:	95							

Appendix Table 12 Uncertainty analysis, and impact assessment of the dry texturing of one 4.3 W wafer

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2,5%	97,5%	Std.err.of mean
Abiotic depletion	kg Sb eq	0,000152	0,000149	0,0000246	16,2%	0,000112	0,00021	0,00514
Acidification	kg SO_2 eq	0,000202	0,000178	0,0000923	45,6%	0,000118	0,000463	0,0144
Eutrophication	kg PO_4--- eq	0,0000784	0,0000683	0,0000447	57%	0,0000333	0,000195	0,018
Fresh water aquatic ecotox.	kg 1,4-DB eq	0,0168	0,015	0,008	47,6%	0,00866	0,0347	0,015
Global warming (GWP100)	kg CO_2 eq	0,0207	0,0204	0,00331	16%	0,0155	0,0286	0,00506
Human toxicity	kg 1,4-DB eq	0,0362	0,0313	0,0202	55,8%	0,0148	0,088	0,0176
Marine aquatic ecotoxicity	kg 1,4-DB eq	36,1	31,7	20,4	56,4%	16,8	85,4	0,0178
Ozone layer depletion (ODP)	kg CFC-11 eq	1,07E-09	1,02E-09	2,79E-10	26%	6,55E-10	1,74E-09	0,00823
Photochemical oxidation	kg C_2H_4 eq	0,00000841	0,00000742	0,00000375	44,6%	0,00000482	0,000019	0,0141
Terrestrial ecotoxicity	kg 1,4-DB eq	0,000188	0,000173	0,0000673	35,7%	0,000102	0,000362	0,0113
Confidence interval:	95							

Appendix Table 13 Uncertainty analysis, and impact assessment of the dry texturing of one 4.5 W wafer

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2,5%	97,5%	Std.err.of mean
Abiotic depletion	kg Sb eq	0,000155	0,000151	0,0000262	17%	0,000111	0,000213	0,00536
Acidification	kg SO_2 eq	0,000207	0,000185	0,0000875	42,3%	0,000119	0,000433	0,0134
Eutrophication	kg PO_4--- eq	0,0000764	0,0000681	0,0000386	50,5%	0,0000318	0,000166	0,016
Fresh water aquatic ecotox.	kg 1,4-DB eq	0,0172	0,0157	0,009	52,4%	0,00823	0,0335	0,0166
Global warming (GWP100)	kg CO_2 eq	0,0211	0,0207	0,00358	17%	0,0151	0,0294	0,00536
Human toxicity	kg 1,4-DB eq	0,0369	0,0325	0,0194	52,5%	0,0149	0,083	0,0166
Marine aquatic ecotoxicity	kg 1,4-DB eq	36,5	32,1	18,3	50,2%	16,7	79,5	0,0159
Ozone layer depletion (ODP)	kg CFC-11 eq	1,08E-09	1,03E-09	2,84E-10	26,2%	6,54E-10	1,77E-09	0,00829
Photochemical oxidation	kg C_2H_4 eq	0,00000862	0,00000774	0,00000358	41,6%	0,0000049	0,0000188	0,0131
Terrestrial ecotoxicity	kg 1,4-DB eq	0,000195	0,000183	0,0000706	36,2%	0,000103	0,000366	0,0115
Confidence interval:	95							

Appendix IV - Water consumption tables of results

Appendix Table 14 Water consumption inventory results, both direct and indirect, for the acidic texturing of one 4.3 W wafer (total does not include: water, cooling, unspecified natural origin/m^3, or water, turbine use unspecified origin/m^3)

Acidic Texturing - 4.3 W per wafer											
Substance	Unit	Total	**DI - water**	**HF - 50**	**HNO_3 - 69**	**HCL - 37**	**KOH - 50**	**NaOH - 50**	**HF waste disposal**	**Electricity**	**Waste water**
Water, cooling, unspecified natural origin/m^3	cm^3	875.030066	9.7417028	165.751694	18.6811553	3.89934424	3.14274449	65.0234466	502.826075	103.384311	2.57959355
Water, lake	cm^3	58.5970802	57.117655	0.74230502	0.03706533	0.00081738	0.01895085	0.01270247	0.40334967	0.0474811	0.21675335
Water, river	cm^3	317.338544	144.233341	36.0184051	4.07448049	0.27126366	0.88275468	4.18756729	104.662942	21.8537264	1.15406371
Water, salt, ocean	cm^3	26.3470985	0.19062847	5.0547577	1.64490913	0.04061864	0.09214791	0.64727651	15.3376138	3.27950758	0.05963877
Water, salt, sole	cm^3	2.87569183	0.00725368	0.54088539	0.58408987	0.00169171	0.00598181	0.02021722	1.64163024	0.06905812	0.00488379
Water, turbine use, unspecified natural origin	dm^3	210.054652	2.04034601	41.6243748	6.75256377	0.2880095	0.67155149	5.0349685	126.28529	26.4065633	0.95098418
Water, unspecified natural origin/m^3	cu.in	181.558632	0.05567523	44.5394	1.40115864	0.01537256	0.01025696	0.23639422	135.19817	0.04696891	0.05523612
Water, well, in ground	cm^3	154.271964	114.471013	8.97944512	1.10493059	0.05710866	0.1617644	0.99342805	23.5497423	4.44794558	0.50658666
Conditioned											
Water, cooling, unspecified natural origin/m^3	l	0.87503007	0.0097417	0.16575169	0.01868116	0.00389934	0.00314274	0.06502345	0.50282607	0.10338431	0.00257959
Water, lake	l	0.05859708	0.05711766	0.00074231	3.7065E-05	8.1738E-07	1.8951E-05	1.2702E-05	0.00040335	4.7481E-05	0.00021675
Water, river	l	0.31733854	0.14423334	0.03601841	0.00407448	0.00027126	0.00088275	0.00418757	0.10466294	0.02185373	0.00115406
Water, salt, ocean	l	0.0263471	0.00019063	0.00505476	0.00164491	4.0619E-05	9.2148E-05	0.00064728	0.01533761	0.00327951	5.9639E-05
Water, salt, sole	l	0.00287569	7.2537E-06	0.00054089	0.00058409	1.6917E-06	5.9818E-06	2.0217E-05	0.00164163	6.9058E-05	4.8838E-06
Water, turbine use, unspecified natural origin	l	210.054652	2.04034601	41.6243748	6.75256377	0.2880095	0.67155149	5.0349685	126.28529	26.4065633	0.95098418
Water, unspecified natural origin/m^3	l	2.97524921	0.00091236	0.7298789	0.02296116	0.00025191	0.00016808	0.00387385	2.21552808	0.00076969	0.00090517
Water, well, in ground	l	0.15427196	0.11447101	0.00897945	0.00110493	5.7109E-05	0.00016176	0.00099343	0.02354974	0.00444795	0.00050659
Total (excluding cooling and turbine use)	**l**	**3.53467959**	**0.31693226**	**0.7812147**	**0.03040663**	**0.00062341**	**0.00132968**	**0.00973505**	**2.36112335**	**0.03046741**	**0.002847**

Appendix Table 15 Water consumption inventory results, both direct and indirect, for the alkaline texturing of one 4.5 W wafer (total does not include: water, cooling, unspecified natural origin/m^3, or water, turbine use unspecified origin/m^3)

Alkaline Texturing - 4.5 W per wafer

Substance	**Unit**	**Total**	**DI - water**	**Singulus Metatex, Solnowat**	**KOH - 50**	**HCL - 37**	**HF - 50**	**HF waste disposal**	**Electricity**	**Waste water**
Water, cooling, unspecified natural origin/m^3	cm^3	777.513059	101.444111	205.26607	91.9776554	18.7761902	8.98467124	224.166304	104.86123	22.0368274
Water, lake	cm^3	597.681232	594.788188	0.21459499	0.55462812	0.00393585	0.04023709	0.17981845	0.0481594	1.85167009
Water, river	cu.in	98.9205033	91.6550894	0.68834875	1.57656632	0.07970884	0.11914276	2.84737347	1.35264791	0.6016259
Water, salt, ocean	cm^3	17.9110948	1.98508788	2.08601921	2.69686228	0.19558759	0.27399621	6.83770467	3.32635769	0.50947924
Water, salt, sole	cm^3	1.34728951	0.07553539	0.21559603	0.17506766	0.00814593	0.02931902	0.73185979	0.07004466	0.04172102
Water, turbine use, unspecified natural origin	dm^3	149.503042	21.2469106	13.751533	19.6540735	1.38682834	2.25627452	56.2996	26.7837999	8.12402186
Water, unspecified natural origin/m^3	cu.in	65.5371604	0.57976762	1.37631429	0.30018696	0.07402222	2.41428523	60.2730757	0.0476399	0.47186845
Water, well, in ground	cu.in	74.4328613	72.7422029	0.17519801	0.28890506	0.01678096	0.02970248	0.64067482	0.27530794	0.26408911
Conditioned										
Water, cooling, unspecified natural origin/m3	l	0.77751306	0.10144411	0.20526607	0.09197766	0.01877619	0.00898467	0.2241663	0.10486123	0.02203683
Water, lake	l	0.59768123	0.59478819	0.00021459	0.00055463	3.9358E-06	4.0237E-05	0.00017982	4.8159E-05	0.00185167
Water, river	l	1.62103639	1.50197613	0.01128015	0.02583561	0.00130621	0.00195242	0.04666066	0.0221662	0.009859
Water, salt, ocean	l	0.01791109	0.00198509	0.00208602	0.00269686	0.00019559	0.000274	0.0068377	0.00332636	0.00050948
Water, salt, sole	l	0.00134729	7.5535E-05	0.0002156	0.00017507	8.1459E-06	2.9319E-05	0.00073186	7.0045E-05	4.1721E-05
Water, turbine use, unspecified natural origin	l	149.503042	21.2469106	13.751533	19.6540735	1.38682834	2.25627452	56.2996	26.7837999	8.12402186
Water, unspecified natural origin/m^3	l	1.07397474	0.00950081	0.02255403	0.00491924	0.00121302	0.03956353	0.98771079	0.00078069	0.00773263
Water, well, in ground	l	1.21975093	1.19204567	0.00287102	0.00473436	0.00027499	0.00048674	0.01049891	0.00451154	0.0043277
Total (excluding cooling and turbine use)	**l**	**4.53170167**	**3.30037142**	**0.0392214**	**0.03891577**	**0.00300189**	**0.04234625**	**1.05261974**	**0.03090299**	**0.0243222**

Appendix Table 16 Water consumption inventory results, both direct and indirect, for the dry texturing of one 4.3 W wafer (total does not include: water, cooling, unspecified natural origin/m^3, or water, turbine use unspecified origin/m^3)

Dry Texturing - 4.3 W per wafer								
Substance	**Unit**	**Total**	**HF waste disposal**	**F$_2$**	**N$_2$**	**CDA**	**Electricity**	**Waste water**
Water, cooling, unspecified natural origin/m^3	cm^3	595.761239	16.1003422	249.54476	45.8003866	129.48343	154.633391	0.19892891
Water, lake	mm^3	574.994335	12.915137	125.868246	15.5971122	332.880451	71.0181558	16.7152331
Water, river	cm^3	122.447779	3.35127644	51.4988987	7.82055824	27.0011178	32.6869307	0.08899721
Water, salt, ocean	cm^3	17.9389033	0.49110586	7.93516586	1.2227988	3.38002729	4.90520634	0.00459913
Water, salt, sole	mm^3	675.170288	52.5645146	318.731239	26.5873199	173.61938	103.291214	0.37662032
Water, turbine use, unspecified natural origin	dm^3	167.473593	4.04361763	59.8918253	8.96839596	54.9997433	39.496674	0.07333645
Water, unspecified natural origin/m^3	cm^3	326.740048	70.9396718	241.353657	0.29237817	12.9333131	1.151225	0.06980247
Water, well, in ground	cm^3	27.1689772	0.75405578	11.9402025	1.82693537	5.9558617	6.65285575	0.03906613
Conditioned								
Water, cooling, unspecified natural origin/m^3	l	0.59576124	0.01610034	0.24954476	0.04580039	0.12948343	0.15463339	0.00019893
Water, lake	l	0.00057499	1.2915E-05	0.00012587	1.5597E-05	0.00033288	7.1018E-05	1.6715E-05
Water, river	l	0.12244778	0.00335128	0.0514989	0.00782056	0.02700112	0.03268693	8.8997E-05
Water, salt, ocean	l	0.0179389	0.00049111	0.00793517	0.0012228	0.00338003	0.00490521	4.5991E-06
Water, salt, sole	l	0.00067517	5.2565E-05	0.00031873	2.6587E-05	0.00017362	0.00010329	3.7662E-07
Water, turbine use, unspecified natural origin	l	167.473593	4.04361763	59.8918253	8.96839596	54.9997433	39.496674	0.07333645
Water, unspecified natural origin/m^3	l	0.32674005	0.07093967	0.24135366	0.00029238	0.01293331	0.00115122	6.9802E-05
Water, well, in ground	l	0.02716898	0.00075406	0.0119402	0.00182694	0.00595586	0.00665286	3.9066E-05
Total (excluding cooling and turbine use)	**l**	**0.49554587**	**0.07560159**	**0.31317252**	**0.01120486**	**0.04977682**	**0.04557053**	**0.00021956**

Appendix Table 17 Water consumption inventory results, both direct and indirect, for the dry texturing of one 4.5 W wafer (total does not include: water, cooling, unspecified natural origin/m^3, or water, turbine use unspecified origin/m^3)

Dry Texturing - 4.5 W per wafer								
Substance	**Unit**	**Total**	**HF waste disposal**	**F_2**	**N_2**	**CDA**	**Electricity**	**Waste water**
Water, cooling, unspecified natural origin/m^3	cm^3	603.457166	16.7195862	259.267283	47.9042913	135.505915	143.851884	0.20820608
Water, lake	mm^3	592.422241	13.411873	130.772204	16.3135874	348.363263	66.0665556	17.4947585
Water, river	cm^3	123.923358	3.48017169	53.5053493	8.1798065	28.2569837	30.4078992	0.09314765
Water, salt, ocean	cm^3	18.1385445	0.50999455	8.24432817	1.27896977	3.53723786	4.56320055	0.00481361
Water, salt, sole	mm^3	691.722535	54.5862267	331.14934	27.8086455	181.694701	96.0894386	0.39418425
Water, turbine use, unspecified natural origin	dm^3	170.18226	4.19914138	62.2252731	9.38037175	57.5578709	36.7428467	0.07675655
Water, unspecified natural origin/m^3	cm^3	339.409854	73.6681207	250.757046	0.30580897	13.5348625	1.07095811	0.07305776
Water, well, in ground	cm^3	27.5620864	0.78305793	12.4054052	1.9108582	6.23287852	6.18899857	0.040888
Conditioned								
Water, cooling, unspecified natural origin/m^3	l	0.60345717	0.01671959	0.25926728	0.04790429	0.13550591	0.14385188	0.00020821
Water, lake	l	0.00059242	1.3412E-05	0.00013077	1.6314E-05	0.00034836	6.6067E-05	1.7495E-05
Water, river	l	0.12392336	0.00348017	0.05350535	0.00817981	0.02825698	0.0304079	9.3148E-05
Water, salt, ocean	l	0.01813854	0.00050999	0.00824433	0.00127897	0.00353724	0.0045632	4.8136E-06
Water, salt, sole	l	0.00069172	5.4586E-05	0.00033115	2.7809E-05	0.00018169	9.6089E-05	3.9418E-07
Water, turbine use, unspecified natural origin	l	170.18226	4.19914138	62.2252731	9.38037175	57.5578709	36.7428467	0.07675655
Water, unspecified natural origin/m^3	l	0.33940985	0.07366812	0.25075705	0.00030581	0.01353486	0.00107096	7.3058E-05
Water, well, in ground	l	0.02756209	0.00078306	0.01240541	0.00191086	0.00623288	0.006189	4.0888E-05
Total (excluding cooling and turbine use)	**l**	**0.51031799**	**0.07850934**	**0.32537405**	**0.01171957**	**0.05209202**	**0.04239321**	**1|0.0002298**