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Patel, Martin

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Surfactants Based on Renewable Raw Materials

Carbon Dioxide Reduction Potential and Policies and Measures for the European Union

Martin Patel

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biobased products
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Summary

Under the European Commission's European Climate Change Programme, a group of experts studied the possibilities of using more renewable raw materials as chemical feedstock and assessed the related potential for greenhouse gas (GHG) emission reduction. Surfactants were among the products studied. Surfactants are currently produced from both petrochemical feedstocks and renewable resources (oleochemical surfactants). Assuming, in a first step, that total surfactant production in the European Union remains constant until 2010, it was estimated that the amount of oleochemical surfactants could be increased from about 880 kilotons (kt) in 1998 to approximately 1,100 kt in 2010 (an increase of 24%). This substitution reduces the life-cycle CO_2 emissions from surfactants by 8%; the theoretical maximum potential for total substitution is 37%. Because the surfactant market is expected to grow, the avoided emissions will probably exceed 8% of the current life-cycle CO_2 emissions from surfactants. If compared to the CO_2 emissions from the total industrial sector and, even more so, if compared to the total economy, the relative savings are much lower (0.02% to 0.09%). This leads to the conclusion that the increased production and use of biobased surfactants should be part of an overall GHG emission reduction strategy consisting of a whole range of measures addressing both energy demand and supply. This article also discusses policies and measures designed to increase the use of biobased surfactants.

Address correspondence to:
Martin Patel
Department of Science, Technology, and Society
Utrecht University
Padualaan 14
NL-3035 CH Utrecht, The Netherlands
⟨m.patel@chem.uu.nl⟩
⟨www.chem.uu.nl/nws/www/nws.html⟩

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The European Commission's European Climate Change Programme

From mid-2000 to mid-2001, the European Commission oversaw the European Climate Change Programme (ECCP). The goal of the ECCP was to help identify the most cost-effective and environmentally beneficial policies and measures (P&Ms) enabling the European Union (EU) to meet its target under the Kyoto Protocol (UNFCCC 1997), that is, to reduce annual greenhouse gas (GHG) emissions by 8% between 1990 and 2008–2012. Seven technical working groups were established, which dealt with the energy-producing and energy-consuming sectors and with instruments for climate policy (ECCP 2001). Compared to earlier initiatives, it was a novelty of the ECCP that a separate subgroup was established to study the use of renewable raw materials (RRMs) as chemical feedstocks. This is in contrast to renewable energy, which has been on the agenda of the European Commission for several years and has led to various policy targets, among them the increase of biomass use in the EU energy supply from 3% in 1997 to 6% in 2010 (EC 1997). No comparable targets for the use of biomass as a chemical feedstock in the EU exist. By contrast, the U.S. Department of Energy set the goal of producing at least 10% of chemical building blocks from biomass by the year 2010 and to increase this share to 50% by 2050 (U.S. DOE 1998, 1999).

With the subgroup on RRMs, the European Commission has discovered the relevance of an important area of industrial ecology for climate change policy. The new and intensified interest originates from the fact that promising developments have taken place in all three categories of products based on RRMs:

- Mature products that have considerable market volumes already today and a clear potential for further expansion (mainly surfactants)
- Rapidly expanding "newcomers" (e.g., biobased polymers)
- Bulk chemicals and intermediates based on biotechnology, most of which are still in the research and development (R&D) stage

The ECCP subgroup on RRMs concentrated on the first two categories. The potential contribution of the following four RRM products for GHG emission reduction was evaluated: polymers, lubricants, solvents, and surfactants (ECCP 2001; Patel et al. 2002, 2003).

In parallel to these analyses for RRMs, other ECCP working groups studied other areas, such as GHG mitigation potential in the energy supply (e.g., efficiency improvements in electricity and steam production) and on the energy demand side (e.g., fuel shifts and new or optimized industrial processes). Without any measures and structural changes, emissions can be expected to increase because of increased production (see "frozen technology and product mix" in figure 1), although the total of the ECCP measures over all sectors of the economy should ensure a decrease of absolute GHG emissions by 8% by the 2008–2012 time frame (EU Kyoto target). Hence, RRM use should be looked upon as a strategy that can *contribute* to GHG emissions reduction and help to reach the targeted goals in combination with other measures.

Characterization of Surfactants and the Scope of this Article

Surfactants are substances capable of reducing the surface tension of a liquid in which they are dissolved. They are composed of a water-soluble group and a hydrocarbon chain. The water-soluble group is hydrophilic and can be either ionic or nonionic, and the hydrocarbon chain is hydrophobic. Together, these two parts provide the compound with interfacial activity, as the nonabbreviated, now less common term "surface-active agent" indicates. Surfactants are used in detergents and cleaners (54%); as auxiliaries for textiles, leather, and paper (13%); in chemical processes (10%); in cosmetics and pharmaceuticals (10%); in the food industry (3%); in agriculture (2%); and in other areas (8%) (CESIO 2001a). Worldwide production of surfactants amounted to 17 million tons (t)[1] in 2000 (including soap), with expected future growth rates

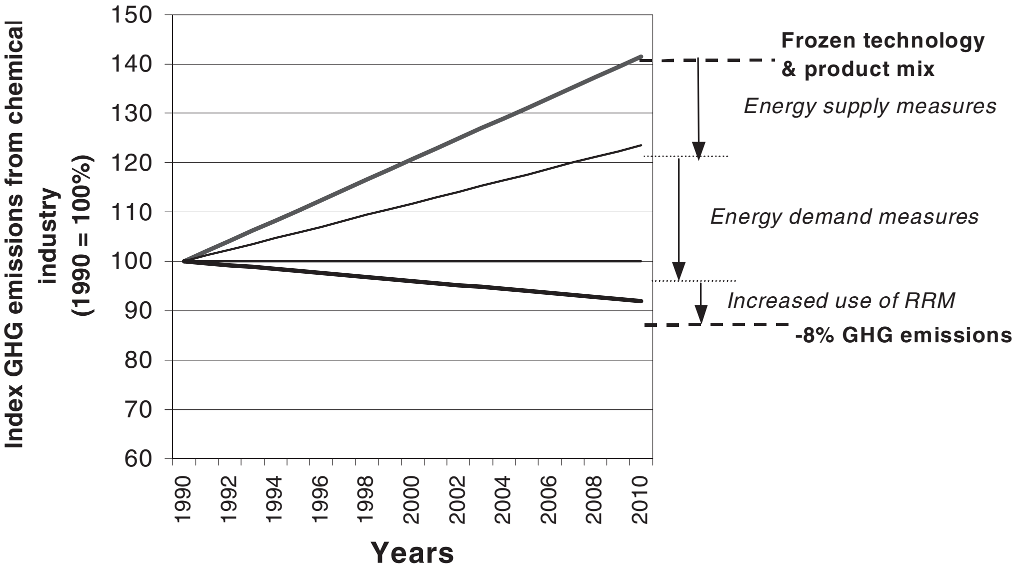

Figure 1 Contribution of various measures to GHG emission reduction.

of 3% to 4% per year globally and of 1.5% to 2.0% in the EU (CESIO 2001a, 2001b; Ward 1996; Whalley 1995).

A surfactant can be categorized according to the electric charge of the portion of the molecule carrying the hydrocarbon chain after dissociation in aqueous solution: anionic (negative charge), cationic (positive charge), nonionic (no charge), and amphoteric (containing both a positive and a negative group). Anionics are commercially the most important class, but they have recently lost some of their market share to nonionics. Nonionics represent the fastest growing type of surfactant because of their increased use in detergents, where they exhibit synergistic effects with other surfactants, and owing to their suitability for the manufacture of highly concentrated detergents or compact products. Cationics (mainly used for fabric softening and liquid household products) and amphoterics (e.g., used for body-care preparations) are limited to comparatively small markets so far (Jakobi et al. 1994).

Soap belongs to the group of anionics. It is the oldest man-made surfactant and is still the leading surfactant at the global level. In industrialized countries, however, soap has been replaced to a large extent by synthetic detergents because of their superior washing properties. Soap also continues to face strong competition in the field of personal hygiene, which represents the largest remaining market. Albeit biobased, soap is excluded from the rest of this article because it cannot be considered a potential substitute for synthetic surfactants as a result of its inferior properties and in view of the ongoing trend toward synthetic surfactants. Cationics and amphoterics are not addressed further either, because the quantities manufactured are relatively small (see below) and because there are no life-cycle data readily available on which to base calculations.

Surfactants represent a particularly interesting product group because they were originally made from renewable resources, whereas today the major part is of petrochemical origin. Still, renewables have not entirely lost their importance, as surfactants are now manufactured from both kinds of feedstocks. Most biobased surfactants are made from vegetable oils and are therefore also referred to as "oleochemical surfactants." The coexistence of biobased and petrochemical surfactants leads to the question of whether the increased use of renewable feedstocks could contribute to the conservation of fossil resources, such as crude oil and natural gas, and hence to the reduction of fossil carbon dioxide (CO_2) emissions. Because surfactants are almost exclusively used in dissipative applications, there is virtually no possibility to capture the embodied carbon and to reuse it. Therefore, the type of carbon source, renewable versus fossil, is decisive when making life-cycle comparisons (cradle to grave). Total life-cycle comparisons must therefore also include emissions that are released in the course of the oxidation of surfactants during wastewater treatment. Apart from these feedstock-related emissions, life-cycle assessments also account for energy use and emissions in agriculture (both direct energy use, e.g., in tractors, and indirect energy use, mainly in fertilizers), chemical processing, and transportation.

In this article, we study the surfactants sector in the EU. First, the current production structure and the associated material and energy requirements are analyzed. This includes an investigation of the quantities of the various intermediates used. Second, a substitution strategy and its possible contribution to reducing CO_2 emissions are presented. Finally, possible P&Ms are discussed.

Current Production

EU production figures are generally only published by surfactant type (e.g., for alcohol sulfates [ASs], alcohol ether sulfates [AESs], or alcohol ethoxylates). A detailed breakdown of production structure, for example, by alcohol chain length or raw material source (e.g., type of vegetable oil), is generally not published because this type of information is considered to be competition sensitive. For the calculations under the ECCP, the European surfactant association Comité Européen des Agents de Surface et leurs Intermédiaires Organiques (CESIO) therefore provided aggregated estimates of the current production volumes (table 1).

The hydrophobic portion of a surfactant is usually produced from either petrochemicals or from RRMs. Surfactants whose hydrophobic portion is based on RRMs account for about 50% of the total production (table 1). A substance flow analysis can be conducted to determine the quantities of the various types of intermediates used. Such an exercise requires a further breakdown of the production data in table 1 by distinguishing between the most important sources of organic raw materials, that is, petrochemical feedstocks, palm oil (PO), palm kernel oil (PKO), and coconut oil (CNO). As a result of the lack of data, the split was based on the same production structure as in Germany (Patel et al. 1999), which accounts for 25% to 30% of the total EU production. This assumption was made on consultation with the industry experts participating in the ECCP subgroup on RRMs. The result of the substance flow analysis is presented in table 2. It shows that RRMs account for about one-third of the total organic feedstock input, with two-thirds of the starting material being of fossil origin.

Future Production

As a part of the activities under the ECCP, CESIO prepared an estimate of the 2010 market potential of oleochemical surfactants. The main drivers and obstacles taken into account are listed in table 3. The estimate was made in two successive steps. In the first step, the share of oleochemical surfactants was assumed to increase, whereas the total production of surfactants in the EU was assumed to remain at 1998 levels (table 4). In the second step, it was assumed that the physical production of surfactants increases by 1.5% to 2.0% per year between 1998 and 2010.

As table 4 shows, substantial changes regarding feedstock choice are considered to be possible until 2010 for ASs, AESs, other anionics, and alcohol ethoxylates. In contrast, it has not been assumed that linear alkylbenzene sulfonates (LASs) and paraffin sulfonates (secondary alkane sulfonates [SASs]) will be substituted by oleochemical surfactants. The CESIO experts expect that oleochemical products will not be able to rival linear alkylbenzene sulfonates (18% of the total surfactant market; table 1) because of its high cost-effectiveness and its specific performance profile (table 4). For SASs (approximately 3% of the total surfactant market; table 1), a constant market share is anticipated (table 4) because of the advantageous properties of this surfactant group (better and faster solubility compared to AESs and ASs, stronger surfactant

Table 1 Production of surfactants in the EU in 1998

	Total production 1998 (kilotons)	*Fraction of total production containing oleochemical compounds (%)*
Anionics		
Linear alkylbenzene sulfonates (LAS)	409	0
Paraffin sulfonates (SAS)	69	0
Alcohol sulfates (AS)	107	60
Alcohol ether sulfates (AES)	246	70
Other anionics	79	40
Total anionics	910	
Nonionics		
Alcohol ethoxylates	638	60
Other ethoxylates	259	90
Amine oxides*	12	80
Other nonionics*	217	30
Total nonionics	1,126	
Cationics		
Esterquats and imidazolinium salts*	115	100
Other cationics*	52	100
Total cationics	167	
Amphoterics		
Betaines*	35	100
Imidazolines*	3	100
Other amphoterics*	17	100
Total amphoterics	55	
Total	2,258	52
Total of products studied further	1,807	49

Note: Soap is not included in this table.

* Excluded from the total of products studied further.

properties, and higher chemical stability for high and low pH values).

Based on these predictions and assuming in the first step that the total EU surfactant market does not grow until 2010, the total production of oleochemical surfactants is projected to increase from about 880 kilotons (kt) in 1998 to approximately 1,100 kt in 2010 (an increase of 24%; table 4). This is equivalent to an increase of oleochemical surfactants by 1.8% per year. The market share of oleochemical surfactants would increase from 49% to 61%, that is, by 1.0% per year on average (table 4). Assuming in a second step that the total surfactant market grows by 1.75% per year (average of 1.5% and 2.0% per year) between 1998 and 2010, total surfactant production is expected to amount to 2,230 kt by 2010. Of this total, 1,350 kt would be oleochemical surfactants.

Note that the assumed increase of oleochemical surfactants will most likely be possible only by use of coconut, palm, and palm kernel oil because, according to the current state of the art, alcohols with short C-chains are required for the manufacture of surfactants. Substantial technological progress would need to be made in order to be able to also use *European* vegetable oils for surfactant production. This is not impossible given the progress that has, for example, recently been made in producing directly ethoxylated fatty acid methyl esters, indicating the applicability of oleochemical raw materials with longer carbon chains (C_{18}), such as rapeseed oil and soya (soybean) oil (Hreczuch 2001).

Table 2 Consumption of primary intermediates for the production of the most important surfactants in Europe in 1998 (various sources)

	Petrochemical intermediates (kt)						*Biomass-derived intermediates (kt)*			
	Benzene	*n-Paraffin*	*Ethylene for olefins*	*Ethylene for ethylene oxide*	*Ethylene for alcohol*	*Methanol*	*Crude PKO*	*Crude CNO*	*Crude PO*	*Glucose monohydrate*
LAS	102.7	211.0								
SAS-Pc		47.0								
AS-Pc		5.3	13.5		9.5					
AS-PKO						0.8	33.2			
AS-CNO						0.3		10.9		
AS-PO						0.0			0.0	
AE_3S-Pc		23.9	19.8	31.5	10.8					
AE_3S-PKO				16.1		0.6	28.6			
AE_3S-CNO				40.2		1.6		71.2		
AE_3-Pc		39.6	72.2	80.6	34.5					
AE_3-PKO				91.4		3.4	166.7			
AE_3-CNO				32.6		1.2		59.3		
AE_7-Pc		3.0	5.5	11.7	2.5					
AE_7-PO				55.8		0.9			48.1	
AE_7-CNO				27.9		0.5		24.0		
AE_{11}-PO				30.9		0.3			19.9	
Total*	102.7	329.8	111.0	418.7	57.2	9.6	228.5	165.4	68.1	0.0

Note: No data were available for AE_7-PO. I therefore assumed that specific material inputs are equivalent to those of AE_7-PKO, for which data are available. The surfactants listed are manufactured from petrochemical and/or oleochemical raw materials. All oleochemical raw materials are produced abroad and imported to Europe. Abbreviations: AE = alcohol ethoxylate; AES = alcohol ether sulfate; AS = alcohol sulfate; LAS = linear alkylbenzene sulfonate; Pc = petrochemical feedstock; PKO = palm kernel oil; CNO = coconut oil; PO = palm oil; SAS = secondary alkane sulfonate.

* Total for petrochemical intermediates = 1,029.0 kt; total for biomass-derived intermediates = 461.9 kt.

Table 3 Drivers and obstacles concerning the further increase of surfactants based on RRMs in the future

Drivers	*Obstacles*
1. Nonionic surfactants represent the fastest growing subgroup; oleochemical raw materials are particularly suited to produce this type of surfactant (compare table 4)	1. More stringent toxicity requirements call for shorter chain lengths than available in vegetable oils
2. CO_2 mitigation, use of renewable resources	2. Price fluctuations of vegetable oils, unclear stability of supply of vegetable oils (e.g., destruction of plantations by fires); relatively secure and stable situation for petrochemicals
3. Synergistic effects between certain RRM-based surfactants and petrochemical surfactants support the growth of oleochemical surfactants, whereas they tend to slow down or even reduce the use of petrochemical surfactants	3. Biodiversity considerations regarding vegetable oil plantations (monocultures), unclear net socioeconomic impacts
4. Progress in plant breeding makes it probable that vegetable oils with more suitable specifications for the surfactant industry can be grown in Europe in the medium term; if, on the other hand, new advantageous crop properties involve genetic modification, serious public resistance may arise	4. Further considerable potentials for the optimization of production processes, and hence the reduction of environmental impacts exist not only for RRM-based surfactants but also for petrochemical surfactants (this is not an obstacle, but it reduces the relative advantage of surfactants based on RRMs)
5. In the last few years, oleochemical surfactants have contributed more to the development of compact detergents and the reduction of washing temperatures than petrochemical surfactants have	5. New plants for petrochemical surfactants (especially LASs) are generally very efficient and very large (e.g., one single world-scale plant can satisfy one-third of the demand of the entirety of North America); consequences of the large size are large market shares of single plants and a strong pressure to recoup the investment
6. From a purely technical point of view, a very large interchangeability of petrochemical and RRM-based surfactants exists (Patel et al. 1999), which is not reflected for LASs and SASs in the projections assumed (table 4), that is, the assumptions made for LASs and SASs are conservative	

Fossil CO_2 Emissions

Some years ago, the European Life-Cycle Inventory (LCI) Surfactant Study Group prepared widely acknowledged LCIs for the manufacture of surfactants (Stalmans et al. 1995; Berna et al. 1995; Hirsinger and Schick 1995; Thomas 1995; Berenbold and Kosswig 1995; Schul et al. 1995). The system covered in these studies reaches from raw material extraction to the factory gate ("cradle to gate"), whereas emissions from the final disposal of the surfactants are excluded. The latter were included in a later analysis (Patel et al. 1999) that evaluated surfactant production/use from raw material extraction to degradation ("cradle to grave"). This article builds on the latter analysis to calculate *total* CO_2 emissions from surfactants, which are referred to as "life-cycle

Table 4 Potential to substitute petrochemical by oleochemical surfactants in the EU by 2010 according to CESIO

	EU production 1998 (kt)	*High-RRM scenario 2010 (kt)*	*Change (%)*
Anionics			
LAS—Pc	409	409	0
SAS—Pc	69	69	0
AS—Pc	43	16	−63
AS—oleochemical	64	91	+42
AE$_3$S—Pc	74	37	−50
AE$_3$S—oleochemical	172	209	+21
Other anionics—Pc	47	28	−42
Other anionics—oleochemical	32	51	+63
Nonionics			
AE—Pc	255	128	−50
AE—oleochemical	383	510	33
Other ethoxylates—Pc*	26	26	0
Other ethoxylates—oleochemical†	233	233	0
Total	1,807	1,807	—
Oleochemical surfactants	884 (49%)	1095 (61%)	+24
Petrochemical surfactants	923 (51%)	712 (39%)	−23

Note: This table covers only the most important surfactants while cationic, amphoteric and some of the nonionic surfactants are excluded (compare with Table 1); for abbreviations see caption of Table 2.

* Containing 7 ethylene oxide (EO) units on average.

† Average of 7 EO units based on PKO and CNO and 11 EO units based on PO.

CO_2 emissions." Strictly speaking, the study still represents a partial analysis because it excludes the energy requirements and emissions associated with the further processing of surfactants (e.g., the production of detergents) and it also excludes the processes in which the surfactants are consumed (e.g., operation of washing machines). These system choices were made for pragmatic reasons, because the wide range of surfactant use does not allow consideration of all types of surfactant processing and use.

Based on the production data in table 1 and the LCI data for the various surfactant types, the total life-cycle emissions related to surfactant production/use in the EU have been estimated at 6.5 million tons of fossil CO_2 in 1998 (figure 2). In the same year, 1.5 million tons of CO_2 emissions were avoided by the production of oleochemical surfactants. This figure was determined by calculating the effect of replacing all oleochemical surfactants by petrochemical products, for which the weighted average of fossil CO_2 emissions amounted to 4,380 kg/ton in 1998 (total of fuel-related and feedstock-related CO_2).

Carbon dioxide emissions for the year 2010 have been determined both for the case assuming that total surfactant production remains at the 1998 level (figure 2, bars 2 and 3) and for the more realistic case assuming a physical average growth in the EU of 1.75% per year between 1998 and the 2010 level (figure 2, bars 4, 5, and 6). For the future mix of surfactants by types of oleochemical raw materials (e.g., shares of AS-PKO, AS-CNO, and AS-PO), the current shares in Germany were assumed (Patel et al. 1999). This assumption was again made on consultation with the industry experts in the working group. On this basis, it was calculated that the increased share of oleochemical surfactants (see table 4) enables a CO_2 reduction of 8.2% (figure 2, bars 2 and 5). If the surfactant sector does not grow, this substitution translates into CO_2 savings of 530 kt (figure 2, bar 2). Taking into account current growth expectations, the CO_2 savings are

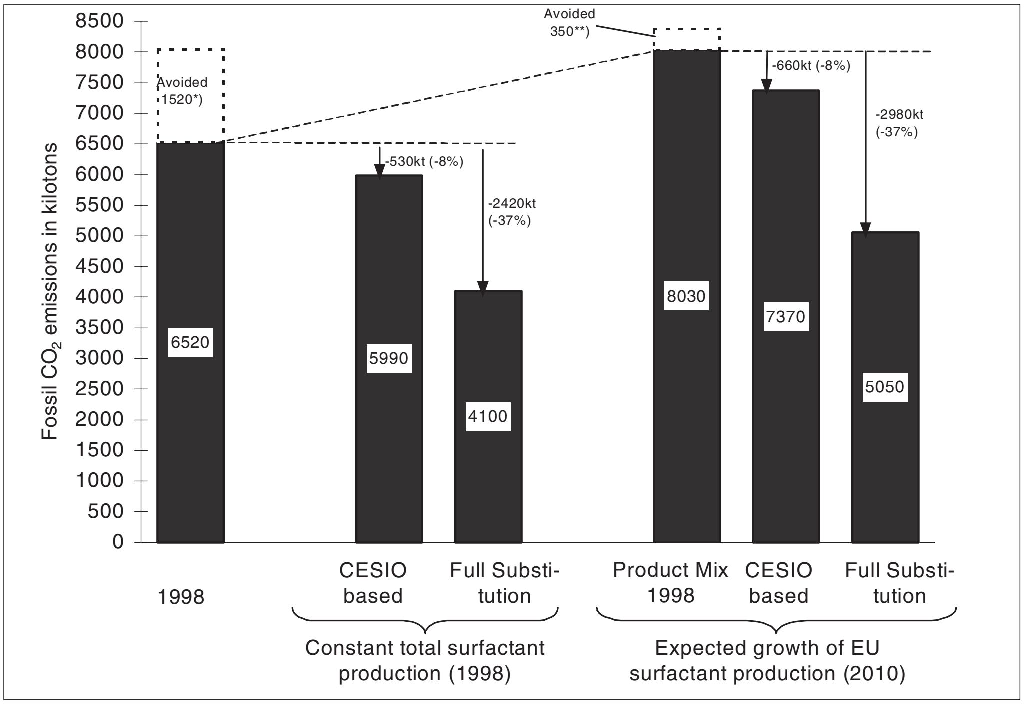

Figure 2 CO_2 emissions related to surfactants in the EU, 1998–2010. All data refer to a selection of the most important surfactants in the EU (without soap), which, in total, amounted to 1,807 kt in 1998 (table 1). The differences in height among the bars originate exclusively from differences in the total production of surfactants and the product mix, that is, the share of oleochemical surfactants (table 4). Other measures to mitigate GHG emissions (i.e., mainly energy efficiency improvement and fuel shifts in the chemical processes involved) in electricity generation and in steam production have not been taken into account. Asterisks indicate CO_2 emissions avoided as a result of production of oleochemical surfactants, relative to no use of RRMs, that is, relative to the exclusive production of petrochemical surfactants. Double asterisks indicate CO_2 emissions avoided as a result of increased production of oleochemical surfactants between 1998 and 2010.

estimated at 660 kt (assuming the same production structure as in 1998; figure 2, bar 5). In absolute terms, this leads to an estimate of total fossil CO_2 emissions of 7,370 kt (bar 5), a value that exceeds the total emissions in 1998 (6,520 kt) by a considerable margin (13%). This shows that although emission reductions can be realized by increasing the share of biobased feedstocks, simultaneous economic growth can easily result in a net increase in emissions.

Figure 2 also contains CO_2 estimates for the theoretical scenario of replacing *all* petrochemical surfactants by oleochemical surfactants (bars 3 and 6). The emission reduction potential of 37% or 2,980 kt represents an overestimation of the available emission reduction potential according to the current state of the art, because the complete replacement of petrochemical surfactants would require additional R&D and may not be feasible for all products. These results are useful, however, because they show the limits of CO_2 mitigation by biobased surfactants.

Common practice in model-based studies of energy efficiency and emission reduction is to measure the effect of P&Ms relative to a so-called reference scenario. The reference scenario is sometimes also referred to as the "baseline scenario" ("baseline" for short) or "business-as-usual scenario." It usually implies that no additional P&Ms are implemented but that the average efficiency of the technologies used improves at a similar rate as observed in the past (so-called autonomous technological progress) and that the product mix also follows a plausible trend. In this study, a constant share of RRMs for surfactant production has been chosen as the reference scenario. This is represented by the fourth bar in figure 2. As an alternative, the reference scenario could have been based on the assumption that the RRM use in *absolute* terms remains constant (with rising production, the latter case means that the RRM share declines). The choice of a constant RRM *percentage* as the reference scenario in this article was made based on past trends and expert expectations for the future.

The two options for the reference scenario are represented by the upper lines in figure 3 (for simplicity, interpolated between 1998 and 2010). The lower line represents the development of emissions if the share of oleochemical surfactants is increased to the CESIO estimate (table 4). As a result of the choice made for the reference scenario (constant percentage of RRM input), P&Ms devoted to an increased use of RRMs contribute an emission reduction of 660 kt CO_2 by 2010. In addition, RRMs lead to an autonomous, growth-related reduction (or rather, avoidance) of 350 kt CO_2 emissions (figure 3). Without growth of the surfactant sector, the savings amount to 530 kt CO_2 by 2010.

Compared to the EU's total current fossil CO_2 emissions (3.3 billion tons in 1998, according to Gugele and Ritter [2002]), these savings account for about 0.2% (a rounded value that applies both with and without growth of the surfactant sector). In the case of total substitution of *all* petrochemical surfactants by oleochemical surfactants, the CO_2 savings would account for 0.07% to 0.09%, depending on whether the overall surfactant production increases (0.09%) or not (0.07%). The potential savings can also be put into perspective by comparing them to the direct emissions from all manufacturing industries and construction, which amounted to 750 million tons of CO_2 in 1998 (direct emissions including process emissions but excluding indirect emissions related to power use [Gugele and Ritter 2002]). Using this basis, the savings are equivalent to 0.07% to 0.09% (for total substitution, 0.3% to 0.4%). Finally, the savings can be compared to the total life-cycle CO_2 emissions of surfactants in Europe, which amount to 6.5 million tons. Relative to this total, the savings of 530 kt (without growth) are equivalent to 8%, whereas the savings with growth (660 kt) represent 10% (figures 2 and 3).

The low-percentage reductions relative to total industrial sector CO_2 emissions and especially relative to the emissions of the entire economy show that a (rather moderate) shift toward more biobased surfactants must be seen as only *one* component in an overall GHG emission reduction strategy. In order to arrive at meaningful savings at the macroeconomic level, a whole package of measures is needed both on the energy supply side and on the energy demand side. Re-

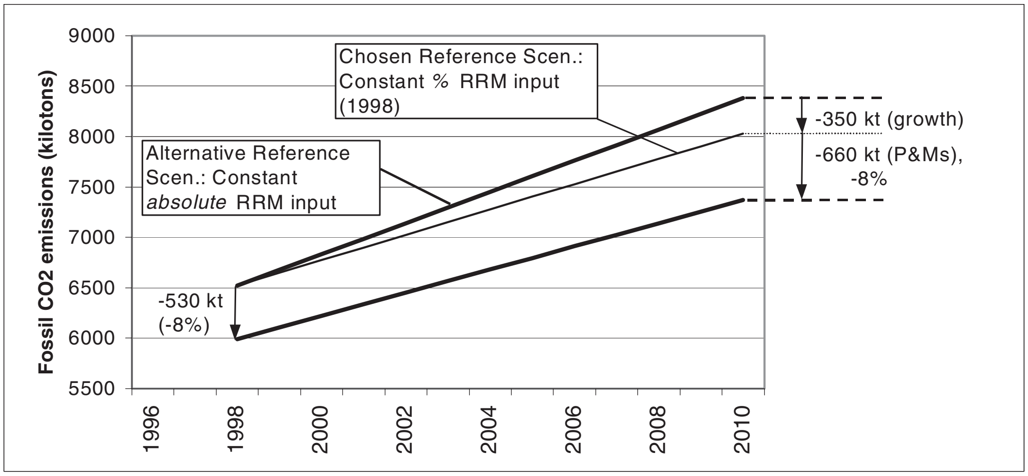

Figure 3 Baselines for fossil CO_2 emissions related to surfactants in Europe.

garding savings on the energy demand side (including feedstocks), it is necessary to make use of both standard energy efficiency measures (e.g., insulation of buildings) and other biobased materials apart from surfactants.

It must be taken into consideration that this analysis excludes important GHGs other than CO_2, particularly CH_4 and N_2O. The reason for this omission is mainly a lack of data, especially for degradation and the in-use phase. An earlier estimate based on the available information (Patel et al. 1999) showed that, depending on the choice of the oleochemical surfactants substituting for petrochemical surfactants, CH_4 emissions either hardly increase (for CNO-based surfactants) or they do increase (for PO- and PKO-based surfactants) but can be reduced by simple technological measures. No conclusions could be drawn regarding N_2O. The impact of biobased surfactant substitution on emissions of these other important GHGs should be addressed by future analysis.

Policies and Measures

In order to increase the share of biobased surfactants, P&Ms can be implemented that help to overcome the obstacles listed in table 3 and that take advantage of the drivers identified (table 3). The final goal is the secure, sufficient, and stable supply of competitively priced vegetable oils of appropriate chemical composition. As a prerequisite, all the sectors and actors involved have to cooperate closely. Table 5 provides an overview of P&Ms that can contribute to the achievement of these goals for surfactants. In general terms, the key components are as follows:

- Medium and longer term research, development, and demonstration to prepare the ground for the competitive use of domestic vegetable oils for surfactant production
- Identification of the areas of competition and complementarity between bioenergy and biomaterials, for example, by means of life-cycle assessments
- Creation of a stronger link between strategies and policies supporting RRMs on the one hand and climate and product policy on the other (e.g., by integration of RRM targets in voluntary agreements for GHG emission reduction)
- Integration of targets related to biobased materials in the Common Agricultural Policy and increased cooperation of the chemical and the agricultural sector
- Awareness raising for biobased materials, because this option for GHG emission reduction is still hardly perceived
- Limited fiscal and monetary support and public procurement for certain product areas with subcritical volumes

Ideally, a rigorous cost-benefit analysis would be required before making decisions regarding specific P&Ms and their implementation. To date, such a comparative analysis has not been conducted for the wide range of options that is available for manufacturing biobased materials. Although this may be considered as prohibitive for policy action, the following aspects should be kept in mind:

- Oleochemical surfactants and many other biobased products are already in the marketplace. This means that many products are already competitive in terms of cost and performance. For these products, a further distinction into two categories can be made. The first group consists of products that can be manufactured at the same or lower cost than their petrochemical equivalents. This is the case for most oleochemical surfactants, which represent a large share of total surfactant production (approximately 50%, see table 4). The second group consists of products that can be sold at a premium price because of their specific product properties. Examples among the biobased materials are biodegradable starch polymers and biodegradable lubricants, where product convenience (e.g., flushable hygiene products), lower system cost, and/or a high environmental image translate into a price margin. Certain oleochemical surfactants (e.g., some alkyl polyglucosides) also belong to this group. In these two cases, environmental benefits are

Table 5 P&Ms to facilitate CO_2 reduction by biobased surfactants

		Measures adopted			
Specific objectives	*Proposed measures*	*Government*	*Industry*	*Possible results*	*Comments*
Improve technical and economic performance of surfactants	Promote basic research for new and existing surfactant precursors based on RRMs	X	X	Stimulation of more R&D	Concentrate on realistic approaches
	Promote applied research, demonstration projects	X	X	Easier decisions for major investments	
Steer innovation and implementation in an environmentally sound direction	Conduct life-cycle assessments of candidate research, development, and demonstration program	X	X	• Minimize environmental impacts of new processes and products (including minimization of GHG emissions) • Continuous improvement of existing processes and products	
Include CO_2 reduction due to oleochemical surfactants in climate policy	Inclusion of GHG mitigation related to oleochemical surfactants in voluntary agreements of the chemical sector at the national (and EU) level	X	X	• Cost minimization of GHG mitigation in the energy versus feedstock area • Awareness raising for RRMs within and outside the chemical sector • In the longer term: inclusion in company policy	
Provide secure, sufficient, and stable supply of competitively priced vegetable oils of appropriate chemical composition for surfactant production	Inclusion of RRMs in future Common Agricultural Policy	X			Requires R&D in both the chemical industry and in the agricultural sector to ensure that domestic vegetable oils can be used for surfactant production

Incorporation of RRM goals by detergent producers in their policy	For example, voluntary agreement of AISE to increase the share of RRM-based surfactants (relative to the total surfactant content of their detergents) by an average of 1.0% per year over a total period of 10 years		X	Could ultimately lead to a tangible reduction of CO_2 emissions	The current AISE (1997) code of good environmental practice for household laundry detergents, which runs from January 1997 to December 2001, contains reduction goals for the energy used in the washing process, for per capita detergent consumption, for per capita packaging consumption, and for biodegradability performance; RRMs are currently not addressed
Stimulate cooperation between the agricultural sector and chemical industry concerning joint projects to utilize European RRMs	Increased focus for RRMs in national and EU R&D programs	X	X	Ownership of technology and patent right could represent barrier	
Facilitate further market penetration of products containing RRM-based surfactants	Increased price attractiveness, for example, by reduced value-added tax rate for surfactants based on RRMs	X			
Stimulate demand and consumer awareness for end products based on RRMs	For example, by public procurement favoring RRM-based end products and by awards (environmental prices)	X	X	Facilitating an economy of scales for producers	
Ensure coherent approach and political attention	Create European Commission interservice task force, White Paper on RRM	X			

reached at zero or very low specific costs (defined as savings of GHG emissions divided by additional costs), that is, at a high to very high cost-effectiveness.

- Second, it is well known that policy is frequently not based on rigorous cost-benefit analyses. Apart from incomplete and unreliable data, the reasons may be (economic) growth and employment prospects, long-term sustainability goals, and/or supply security. These and other reasons explain why, for example, renewable energy is being promoted through public policy. Although the basically infinite resource base makes renewable energy comparable to olechemical surfactants, the specific costs are considered to be rather high in most cases. For example, the specific CO_2 abatement cost for bioenergy from cheap biomass and for wind energy amounts to €10/ton CO_2 (equivalent to approximately €0.75/GJ) under most favorable conditions, for solar-thermal energy to €20 to €100/ton CO_2 (equivalent to €1.5 to €7.5/GJ) and to much higher values for most other energy options, especially photovoltaics (€300 to €1,000/ton CO_2 and beyond) (values are based various sources, including research by Fichtner et al. [1996], Kaltschmitt and Wise [1997], and Herzog et al. [1997]). At the same time, numerous measures in the area of energy *conservation* are available at very low or even at negative costs, that is, under profitable conditions (e.g., heat insulation of buildings). Because policy in most countries does not rely on energy conservation *alone* but also on renewable energy, it is justified to judge the societal benefits of oleochemical surfactants (and other biobased materials) relative to renewable energy options.

To summarize, the rationale for endorsing in this article an active policy in favor of oleochemical surfactants is that the use of renewable resources for this purpose is generally more cost-effective than the generation of bioenergy. Other biobased materials apart from surfactants seem to be less cost-effective in terms of GHG emission reduction (at least in the short to medium term). This can be derived from the fact that the prices for biobased materials other than surfactants are relatively high compared to their petrochemical counterparts; however, technological progress is very likely to bring down the prices here also.

A steady increase of the market share of oleochemical surfactants by active policy intervention would likely lead to higher and higher marginal cost (accompanied by decreasing cost-effectiveness). This raises the question of the extent to which oleochemical surfactants should be actively supported. This issue has not been investigated so far and should be addressed by future research. To answer such a research question, large integrated models may be used that take into account a whole range of options (and their dynamics over time) both on the energy supply side and the energy demand side (including materials). Because such an analysis is beyond the scope of the research presented here, a cautious approach is taken in this article by proposing only P&Ms that entail low costs (see bulleted list above and table 5). Critics may argue that the highly cost-effective GHG emission reduction by oleochemical surfactants should lead to the conclusion that policy must not address this group of materials but rather deal with other biobased materials (or entirely other options) for which the challenge of bringing down costs is larger. This type of controversy about preferences and strategies must be addressed in the policy arena. It cannot be solved purely on the basis of scientific and techno-economic analyses but also needs to account for uncertainties in data, unknown boundary conditions, risks, public perception, and numerous other issues.

The proposed P&Ms listed in table 5 can serve as a starting point for policy making and the development of a concrete and coherent strategy, which should also include other biobased materials (mainly lubricants, polymers, solvents, and fibers). A first step in this direction has been made by setting up a task force composed of former members of the ECCP subgroup on RRMs. This RRM task force is composed of experts from companies, nongovernmental organizations, and universities. It is led by the European Raw Materials Association (⟨www.errma.com⟩), and it proceeds in close interaction with the European Commission. It has produced a report (Ehrenberg 2002), according to which the key benefits of biobased materials are advantages for the environment, the provision of a stable and secure resource supply, new and growing markets providing economic benefits to industry, and employment opportunities in processing industries and the agricultural sector. An important step forward is that in June 2002, the Industry and Energy Council of the EU explicitly mentioned RRMs in their conclusions on the contribution of enterprise policy to sustainable development (CEU 2002). As one of its recommendations, the council proposed to build on the report of the RRM task force (Ehrenberg, 2002), and it called on the EU member states and the European Commission to further encourage the use of RRMs in the manufacturing industry (CEU 2002). Now, a key goal of the RRM task force is to initiate a development similar to the United States' Vision 2020, with strategic industry-government alliances that are guided by long-term goals for biobased materials (compare U.S. DOE 1998, 1999).

If a sufficient number of the measures listed are adopted with success, then emissions can be reduced by 660 kt in 2010, which is equivalent to 8% compared to the reference scenario.

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Note

1. One metric ton = 1 Mg (SI) ≈ 1.102 short tons. Unless otherwise indicated, all tons in this article refer to metric tons.

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About the Author

Martin Patel is an assistant professor in the Department of Science, Technology, and Society at Utrecht University in Utrecht, the Netherlands.