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2010
2011

BEDRIJFSECONOMISCHE WETENSCHAPPEN

master in de toegepaste economische wetenschappen: handelsingenieur: technologie-, innovatie- en milieumanagement

Masterproef

Improving photocatalysts towards innovative market applications: an economic analysis

Promotor :
Prof.dr.ir Steven VAN PASSEL

Nathalie Deckers

Masterproef voorgedragen tot het bekomen van de graad van master in de toegepaste economische wetenschappen: handelsingenieur , afstudeerrichting technologie-, innovatie- en milieumanagement

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UNIVERSITEIT VAN DE TOEKOMST

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For the past five years, I have been working hard to become a business engineer. Throughout this period of time, the University of Hasselt has always been an excellent operating base which, to me, is typified best by its conviviality. This university can rely on a firm base of tutors and staff members characterized by a progressive mentality of which my promoter, Prof. dr. ir. Van Passel, is the living proof. Besides propounding me to work on a highly interesting and relevant topic, he also suggested taking part in the Master of Science Thesis Programme organized by the Belgian industrial Research and Development [BiR&D] which requires both technical and non-technical academic faculties to collaborate. This way, I got in touch with Elke Moortgat, who is a bioengineer student in her final year at the Catholic University of Leuven and the University of Antwerp. While she approached the scientific issues (with the assistance of her supervisors Prof. dr. ir. Martens, Prof. dr. Lenaerts and ir. Verbruggen), I focused on the economic ones which merged together perfectly into an interconnected project.

Obviously, if it was not for Prof. dr. ir. Van Passel, I would not have been able to participate in this synergetic project. I sincerely would like to render thanks to him for enabling this, but also for the guidance he gave me the past couple of months. To pull off the project, I had to co-operate intensely with Elke. We always seemed to collaborate effortlessly which cannot be taken for granted when working together with someone you have only just met. I wish her all the best in whatever she decides to strive for in the future. Furthermore, Elke's supervisors, in particular ir. Verbruggen, were always willing to provide me with some complementary scientific information to optimize my understanding of the technical part which I clearly appreciate a lot.

Last but not least, I would like to thank my family and friends. They have supported me throughout my academic career in an unparalleled manner. They always backed up the decisions I took, listened to whatever I had to share and gave me their honest opinion. I am truly grateful to find myself in such a stimulating environment in which I am surrounded by highly inspiring individuals.

Nathalie Deckers, June 2011

ABSTRACT

Indoor air pollution has been estimated to be about two to five times higher than outdoor air pollution. In addition to the previous statement, an average individual may spend up to eighty percent of his time indoors. The problem is especially severe for volatile organic compounds (VOCs) that have been linked to adverse health effects. Obviously, there is a need for methods to reduce the concentration of such pollutants found indoors.

Therefore, the potential of photocatalysis in addressing the problem is examined. A titanium dioxide (TiO_2) semiconductor catalyst which is activated under the influence of ultraviolet (UV) light is applied to degrade acetaldehyde, a specific type of VOC, into water and carbon dioxide. This technical research is extended with theoretical economic insights to examine whether the photocatalytic system presented above would also be commercially viable.

Firstly, all variables influencing the quantity demanded of the technology under investigation are listed. Attention has especially been paid to the broad competitive environment in which the technology will have to emerge. Next to photocatalysts, two other air-cleaning technologies, being gas-phase filters and ozone generators, are described. The prices of these substitutes can be expected to affect the quantity demanded of the photocatalyst. Besides air-cleaning technologies, source control and ventilation measures can also be applied to reduce indoor air pollution. These methods are thus indirect competitors of the technology under investigation. Nevertheless, one method by itself is not capable of reducing all indoor air pollution. Therefore, combinations of the three methods will have to be made in which source control will always be applied before one switches to ventilation and end-of-pipe technologies. So, all factors stimulating individuals to take source control or ventilation measures indirectly determine the need for air-cleaning technologies including the photocatalyst under investigation. Several examples are given to indicate that regulative authorities play a prominent role in this context.

Secondly, all variables influencing the quantity supplied of the photocatalyst under investigation are determined. One topic, the choice of the photocatalytic material (a specific production input), is

dealt with rather extensively. The ideal material has a low cost and shows a high performance. Obviously, these requisites are difficult to reconcile. To address this matter, a cost-effectiveness analysis (CEA) is performed which compares the costs of the possible photocatalytic materials with their ability to convert acetaldehyde into carbon dioxide and water, in other words their effectiveness. This analysis perfectly extends the technical research, is fairly simple to perform and is highly comprehensible. For each material both an average cost-effectiveness ratio (ACER) and an incremental cost-effectiveness ratio (ICER) is calculated. The first ratio compares the cost of each material with its conversion. The material having the lowest ACER will be chosen. The latter compares the cost of each photocatalyst relative to a reference standard with its conversion relative to the same standard. A cost-effectiveness (CE) plane is employed to determine the optimal material. Of all commercially available photocatalysts tested, Millenium (Chrystal Globe) turned out to be the most cost-effective one. This conclusion can be drawn based on the ACERs and ICERs, at both acetaldehyde intake levels tested, irrespective of the catalytic quantity applied and is proven not to be sensitive to fluctuations in Millenium's price. Of all photocatalytic materials produced manually in an academic research centre, the samples prepared according to the third preparation method of Rachel, Subrahmanyam and Boule (2002) with water added for suspending performed best and can be advised. This conclusion holds irrespective of the specific CE ratio consulted, the acetaldehyde intake level applied and the catalytic quantity chosen. The results do not change when the cost per kilowatt-hour, which weighs heavily on badly performing samples, is lowered.

SAMENVATTING

Binnenhuislucht wordt geschat twee tot vijf maal zwaarder vervuild te zijn dan buitenlucht. Daarenboven brengt een gemiddeld individu ook nog eens tot tachtig percent van zijn tijd binnenshuis door. Het probleem stelt zich met name bij vluchtige organische componenten (VOC's) die gekend zijn omwille van hun schadelijke effecten op de menselijke gezondheid. Men kan duidelijk stellen dat er nood is aan methoden die in staat zijn de concentraties aan polluenten binnenshuis te doen dalen.

Het potentieel van fotokatalyse inzake het oplossen van het hierboven toegelichte probleem wordt bestudeerd. Een titaniumdioxide (TiO_2) halfgeleider, die onder invloed van ultraviolet (uv) licht wordt geactiveerd, wordt toegepast om aceetaldehyde (een bepaalde VOC) af te breken tot koolstofdioxide en water. Dit technisch onderzoek wordt aangevuld met theoretische economische inzichten om te bepalen of het beschreven fotokatalytische systeem economisch levensvatbaar is.

Allereerst worden de verscheidene variabelen die de gevraagde hoeveelheid van de technologie onder beschouwing beïnvloeden, bepaald. Hierbij wordt uitgebreid stilgestaan bij de brede concurrentiële omgeving waarin de technologie zal terechtkomen. De fotokatalysator zal moeten concurreren met twee andere luchtzuiverende technologieën, met name de gasfasefilter en de ozongenerator. De prijzen van deze substituten bepalen mede de gevraagde hoeveelheid van de technologie onder beschouwing. Naast de luchtzuiverende technologieën bestaan er twee andere methoden om binnenhuisluchtvervuiling aan te pakken: broncontrole en ventilatie. Deze methoden zijn met andere woorden indirecte concurrenten van de eigen fotokatalysator. Één bepaalde methode is echter niet in staat alle vervuiling weg te nemen. Vandaar dat er combinaties van de drie methoden gemaakt moeten worden waarbij men steeds eerst kiest voor broncontrole en pas daarna voor ventilatie en luchtzuiverende technologieën. Men kan dus stellen dat alle factoren die mensen ertoe aanzetten meer aan broncontrole en ventilatie te doen ervoor zorgen dat er minder nood is aan luchtzuiverende technologieën zoals de fotokatalysator onder beschouwing. Verscheidene voorbeelden duiden aan dat regelgevende instanties een voorname rol spelen in deze context.

Vervolgens worden ook de factoren die de aangeboden hoeveelheid van de eigen technologie beïnvloeden, toegelicht. Behoorlijk wat aandacht wordt besteed aan de keuze van het fotokatalytische materiaal (een bepaalde productie-input). Het ideale materiaal wordt gekenmerkt door een lage kostprijs en een hoge prestatie. Voornoemde vereisten zijn uiteraard moeilijk met elkaar te verzoenen. Om aan deze moeilijkheid het hoofd te bieden wordt er gebruik gemaakt van een kosteneffectiviteitsanalyse (CEA) die de kosten van de materialen afweegt tegen de mate waarin ze in staat zijn aceetaldehyde af te breken tot koolstofdioxide en water, met andere woorden hun effectiviteit. Deze analyse vult perfect het technische onderzoek aan, is behoorlijk eenvoudig uit te voeren en is zeer toegankelijk. Voor ieder materiaal wordt er zowel een gemiddelde kosteneffectiviteitsratio (ACER) als een marginale kosteneffectiviteitsratio (ICER) berekend. De ACER vergelijkt de kost van ieder materiaal met de conversie ervan. Het materiaal met de laagste ACER zal worden gekozen. De ICER vergelijkt de extra kost van iedere fotokatalysator ten opzichte van een referentiestandaard met de extra conversie ervan ten opzichte van diezelfde standaard. Een kosteneffectiviteitsvlak wordt gehanteerd om het meest optimale materiaal te kunnen bepalen. Van alle commercieel beschikbare fotokatalysatoren komt Millenium (Chrystal Globe) er als meest kosteneffectief uit. Deze conclusie kan worden getrokken op basis van zowel de ACERs als de ICERs, beide geteste aceetaldehyde debieten en ongeacht de gebruikte katalytische grootheid. Voorts is deze conclusie niet gevoelig aan schommelingen in de kostprijs van Millenium. Van alle fotokatalytische materialen die manueel werden vervaardigd in een universitair onderzoekscentrum, blijken de stalen die werden geproduceerd volgens de derde bereiding van Rachel, Subrahmanyam and Boule (2002) met toevoeging van water het meest geschikt en deze worden dan ook geadviseerd. Deze conclusie geldt ongeacht de geraadpleegde kosteneffectiviteitsratio, het gehanteerde aceetaldehyde debiet en de gekozen katalytische grootheid. De resultaten veranderen niet wanneer de kost per kilowattuur, die zwaar weegt op slecht presterende stalen, wordt verlaagd.

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LIST OF ABBREVIATIONS

ACER	average cost-effectiveness ratio
Ag	silver
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAT	best available techniques
BiR&D	Belgian industrial Research and Development
BREF	best available techniques reference document
CB	conduction band
CBA	cost-benefit analysis
CE	cost-effectiveness
CEA	cost-effectiveness analysis
CREG	Commission for the Regulation of Electricity and Gas
CRI	the Carpet and Rug Institute
EPA	Environmental Protection Agency
EU	European Union
EU-15	first fifteen countries to join the European Union
HVAC	Heating, Ventilating and Air Conditioning
ICER	incremental cost-effectiveness ratio
LUSS	decision support system to screen techniques capable of reducing air pollution
NAAQS	National Ambient Air Quality Standards
NP	nanoparticles
OAQPS	Office of Air Quality Planning and Standards
OSHA	Occupational Safety & Health Administration
ppmv	part per million by volume
SCS	Scientific Certification Systems
SME	small and medium enterprises
SnO_2	tin dioxide
TiO_2	titanium dioxide

TWA	time weighted average
US	United States
UV	ultraviolet
UVA	ultraviolet A
UVB	ultraviolet B
UVC	ultraviolet C
VB	valence band
VITO	Vlaamse instelling voor technologisch onderzoek / Flemish institute for technological research
Vlarem	Vlaams reglement betreffende de milieuvergunning / Flemish regulation concerning environmental permits
VOC	volatile organic compound

CHAPTER I: INTRODUCTION

Both the increase in energy costs and the drive for a sustainable environment experienced during the past couple of years put people on to sealing buildings more tightly to confine energy consumption. Unfortunately, attended with improved windows, insulation and moldings, the exchange of air between indoor and outdoor environments by means of infiltration (through openings, joints and cracks) and natural ventilation (through open windows and doors) is reduced. This enables pollutants to accumulate in indoor surroundings. As a result, indoor air pollution has been estimated to be about two to five times higher than outdoor air pollution which becomes even more disturbing knowing that an average individual may spend up to eighty percent of his time indoors. Obviously, concerns with regard to human health have been raised (Birnie, Riffat, & Gillott, 2006; Environmental Protection Agency, 2009; Zhang, Yang, & Zhao, 2003).

The problem is especially severe for a certain group of pollutants, being volatile organic compounds (VOCs). On top of the accumulation of pollutants indoors caused by the improved sealing of buildings, people are aggravating the problem even further by using more synthetic building materials, furnishings and consumer products containing VOCs indoors. The fact that high concentrations of these VOCs have been linked to adverse health effects stresses the need to look for ways to reduce the concentration of such pollutants found indoors (Zhang et al., 2003).

Several technologies, of which photocatalytic oxidation is only one example, are being developed to tackle this problem. This technology stems from the discovery of photo-induced water cleavage on titanium dioxide (TiO_2) semiconductor electrodes of Fujishima and Honda about three and a half decades ago. The use of this phenomenon is not only limited to water purification. In fact, photocatalysis can be applied to various environmental remediation causes (including air purification). In each case, a chemical reaction is initiated by light which removes electrons from a solid photocatalyst and adds them to a reactant (the pollutant) that is present in a liquid or gas phase (the process will be explained in more detail later) (Birnie et al., 2006; Zhao & Yang, 2003).

A bioengineer student is looking into the applicability of the technology for the purification of polluted indoor air. Firstly, she has determined which specific type of photocatalyst to test (a TiO_2 semiconductor), what kind of light to apply (ultraviolet (UV) light) and which reactant to target (acetaldehyde, which is a VOC). Secondly, she has evaluated the performance of the photocatalytic material in her test design and finally, she has tried to improve the performance of this material.

Suppose the scientific research would result in a photocatalytic system which performs properly, would this system also be commercially viable? This thesis is build around the previously posed question. To study the economic potential of the technology, both the demand and the supply side of the market are of relevance and will therefore be addressed extensively from a rather theoretical economic point of view. By denominating the different factors of the demand and supply function of the technology, it is made sure that all relevant factors are taken into account. When discussing the demand side of the market on the one hand, the photocatalytic system tested and its direct and indirect competitors will mainly be elaborated on. A considerable amount of attention will be paid to the regulatory framework that will have to be taken into account. When expounding the supply side of the market on the other hand, the most important production input, the photocatalytic material, will be the main concern. In this discussion, a cost-effectiveness analysis (CEA) will be employed to select the most appealing type of photocatalytic material from both a scientific and an economic point of view.

Rarely, the commercial viability of a technology is taken into consideration at such an early stage. So, this thesis applies a rather unique approach towards product development that is built on the belief that technical and economic research which is performed more or less simultaneously leads to synergetic results.

CHAPTER II: DEMAND

2.1 THEORETICAL APPROACH

When new technologies are being developed, it is important to look at several economic aspects. Evidently, a product can only be sold when people wish to purchase it (Lipsey & Chrystal, 2004). So, the product can perform flawlessly, be supplied with a breathtaking design and can even be fairly priced; when the desired quantity of the product is insufficient, all efforts made to complete it turn out to be pointless (at this instant). That is why this thesis focuses on the economic viability of the technology being developed. The economic surroundings in which the technology will have to survive will be mapped.

The previous clearly points out that next to the properties of the technology itself, other factors influence the quantity demanded by consumers. Five variables in particular, being: the price of the product, the prices of other products, the consumer's income and wealth, the consumer's tastes and various individual-specific or environmental factors, can be pointed out. Mathematically, this can be presented as the demand function with the quantity demanded depending on these five variables.

$$q_n^d = D(p_n, p_1, \dots, p_{n-1}, Y, S)$$

In this function q_n^d represents the quantity demanded by consumers of a certain product n. The independent variable p_n is its corresponding price, whereas the remaining p's represent the prices of other products. Two types of related products are extremely relevant: substitutes and complementary goods. Substitutes are products for which an increase in their price results in an increase in the quantity demanded for the product under consideration (and vice versa). Complementary goods, however, experience the opposite effect. When their price increases, this leads to a decrease of the quantity demanded of the product under consideration (and vice versa). The variable Y represents the consumer's income and S comprises several factors that vary from individual to individual. The last variable affecting the quantity demanded, environmental factors, only matters in real time and therefore is left out of consideration (Lipsey & Chrystal, 2004; Pindyck & Rubinfeld, 2005).

The demand function can be reproduced graphically (Figure 1) with the quantity demanded of the product (q_n^d) serving as the dependent variable and its price (p_n) as the independent variable. All other independent variables ($p_1, \dots, p_{n-1}, Y$ and S) are held constant (the ceteris paribus assumption). Contrary to what is expected mathematically, economists normally depict quantity on the horizontal axis and price on the vertical axis.

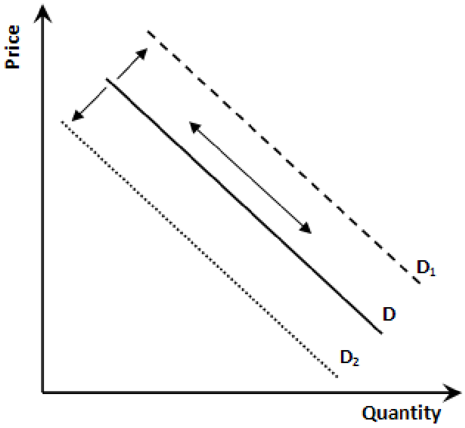

Figure 1. Demand function

When the price of the product changes, the quantity demanded can also be expected to change. Graphically, this will become apparent in a shift along the demand curve D as the double arrow shows. A feature of the demand curve is that price increases (decreases) lead to decreases (increases) in quantity as the negative slope of the function proves. Evidently, common sense leads to the exact same relationship between quantity demanded and price (Lipsey & Chrystal, 2004).

When, on the other hand, one of the remaining independent variables ($p_1, \dots, p_{n-1}, Y$ and S) changes, the demand curve D shifts into a new position. Depending on the type of change, this can be represented by a shift of the curve to the right (e.g. into position D_1) or to the left (e.g. into position D_2). A rise in the price of a substitute product for example, will result in a shift to the right of the demand curve (e.g. into position D_1) because the product under consideration will become relatively more appealing to the customer. Its quantity demanded will thus increase. It is also possible that several or even all remaining independent variables change. In this case, it is more difficult to foresee the exact direction of the movement of the demand curve because some changes can neutralize one another either partially or completely (Lipsey & Chrystal, 2004).

It should be noted that the model which is clarified above presumes perfect competition. This is a market structure which applies to several real-world markets and is often used as a benchmark for comparison with other structures. In a perfectly competitive market several assumptions hold. Firstly, all competing firms sell identical products (product homogeneity). Secondly, all buyers are perfectly informed about the characteristics and price of the product (transparency). Thirdly, each firm has a relatively small market share. Fourthly, a single firm cannot significantly affect the market price and thus is to passively accept it (price-taker). Finally, each firm is free to enter and leave the industry (mobility) (Lipsey & Chrystal, 2004). Although several assumptions clearly do not hold, the model will be used to structure and discuss the different possibilities.

Having approached demand for a product from a theoretical perspective, it is possible to apply the theory to a specific technology. To get an idea of the quantity demanded of that technology, all factors influencing this dependent variable should be pointed out. Several relevant questions have to be answered: At what price can the technology be purchased? Does it have substitutes? Are there products acting as complementary goods? What is the income of a consumer? Which individual-specific factors should be taken into account?

2.2 METHODS TO REDUCE INDOOR AIR POLLUTION

Three different methods to reduce indoor air pollution can be distinguished: source control, ventilation and air-cleaning control (Birnie et al., 2006; Kim, Kang, Choi, Yeo, & Kim, 2008; Environmental Protection Agency, 2009; Zhang et al., 2003).

2.2.1 SOURCE CONTROL

The most effective solution to improve indoor air quality aims at removing the individual sources of pollutants or controlling their emissions (Kim et al., 2008; Environmental Protection Agency, 2009; Zhang et al., 2003). Several indoor air quality management manuals and guidelines suggest source control as the first option to consider when trying to reduce the concentration of pollutants in indoor air (Kim et al., 2008). Unfortunately, this option cannot always be exploited. During the design phase of a building, attention can be paid to the chosen building materials. Low-emission building materials are definitely preferable. Clearly, once the selection procedure of these materials or the construction process of the building is completed, only a limited number of options are left to prevent the emission of pollutants. The inhabitants of the building should keep an eye on the products they use, because several of these products contain polluting substances that can be released into the air. Moreover, they should keep in mind that some of the activities they perform indoors are possible sources of pollutants. Obviously, the emissions due to these pursuits can also be hampered. The nicotine break of smokers can easily take place outside, combustion appliances can be revised to reduce the discharge of harmful combustion products and so on (Kim et al., 2008; Jones, 1999; Environmental Protection Agency, 2009). An interesting comment to make is the fact that pollutants can also be tracked from outside. Luckily, outdoor air quality has obtained a fair amount of attention (United States General Accounting Office, 1999).

2.2.2 VENTILATION

Next to the control of polluting sources to ameliorate indoor air quality, ventilation can be used to reduce the indoor air pollutant concentration. Ventilation ensures air is exchanged between the outside environment and the inside of a building (Kim et al., 2008; Environmental Protection Agency, 2009; Zhang et al., 2003). Two different ventilation methods are possible. The first one, a general ventilation of the living space, comprises infiltration, natural and mechanical ventilation. The denomination 'infiltration' is used when outdoor air enters buildings through openings, joints, and cracks. Natural ventilation brings outdoor air indoors through open windows and doors. A similar effect can be obtained mechanically. General ventilation takes outdoor air indoors, circulates it throughout the building (dilution) and exhausts polluted air outdoors. This leads to an improved air quality. Be sure to notice that dilution on its own decreases the average pollution concentration without completely eliminating the contaminants. This is an important consideration in areas where pollutant emissions are high or air distribution falls short. A second ventilation method, though enforced more locally, has a more or less equivalent operation. In this case, excess moisture and strong, local contaminants are aimed at and their spread into other areas is prevented. This can be achieved by means of exhaust fans in specific rooms (like kitchens and bathrooms) and by open windows and doors. Nowadays, in the design stage of a building, advanced mechanical solutions are also being added. When applying one of both methods, attention should be paid to the quality of the incoming air. This could also be polluted, lowering or eliminating the value of ventilation to dilute or remove indoor pollutants. To conclude, an important downside of ventilation that needs to be signaled, is that it involves energy losses (Kim et al., 2008; Environmental Protection Agency, 2009).

2.2.3 AIR-CLEANING CONTROL

The third method to improve indoor air quality is 'air cleaning'. Mechanical air-cleaning devices or decomposing agents are used to control pollution by means of physical or chemical reactions. Recently, several types of decomposing agents have received growing interest. Photocatalysts, for example, have already proven to be effective (Kim et al., 2008).

2.2.4 COMBINED EXERTION

All three methods (source control, ventilation and air-cleaning control) are capable of reducing indoor air pollution. They do however constitute different means to an end. By controlling the source, indoor air pollution is prevented, whereas ventilation ‘merely’ reduces the indoor air pollutant concentration. The last method, air cleaning, cannot be seen as a substitute to either one of the previous two methods because air cleaners on their own cannot ensure air of sufficient quality. This is especially the case when significant sources are present and ventilation is insufficient. In other words, the three methods are often combined (Environmental Protection Agency, 2009). Clearly, the cited literature suggests that the methods do not act as perfect substitutes to one another due to their differences in effectiveness. Source control can reasonably be expected to be taken under consideration first, followed chronologically by ventilation and air-cleaning control.

Nevertheless, all three methods do bring about a similar effect, videlicet a reduction of indoor air pollution. Thus, the larger the amount of pollution controlled through the application of a certain method, the smaller the amount left to be aimed at through means of one of the remaining methods. This seems to imply the presence of a substitution effect. To give judgment on whether or not this supposition holds, data has to be collected and checked empirically.

One could also suggest denominating the three methods as complementary to one another, given that, as was stated earlier, the methods are often combined when attempting to control indoor air pollution. This would imply that when, for example, air-cleaning technologies become more expensive, less use will be made of the remaining two methods. At first sight, this does not make much sense, though empirical analysis could again remonstrate this postulate.

To check whether or not the methods are either substitutable or complementary, one can apply an economic concept termed the cross elasticity of demand. This concept can mathematically be presented through means of the following formula.

$$\eta_{xy} = \frac{\Delta\, q_x^d \text{ (in \%)}}{\Delta\, p_y \text{ (in \%)}}$$

The cross elasticity of demand (η_{xy}) represents the percentage change in the quantity demanded of product X ($\Delta\, q_x^d \text{ (in \%)}$) due to an increase of one percent in the price of product Y ($\Delta\, p_y \text{ (in \%)}$). A positive elasticity indicates that product X and Y are substitutes, whereas a negative sign suggests that both products are complementary (Lipsey & Chrystal, 2004).

The actual analysis is beyond the scope of this work. Throughout the remainder of this thesis, the three methods will not be denominated as substitutes, nor will they be seen as complementary to one another. Nevertheless, it will be kept in mind that all three methods are applied to fulfil the same need, videlicet obtaining cleaner indoor air. Each method is capable of controlling indoor air pollution at least partially, bearing in mind the fact that these methods differ in term of effectiveness. Therefore, as stated earlier, combinations are often made to reach a sufficient level of indoor air quality. It can be expected that all methods proven to be serviceable in the situation at hand, will fill up the combination in order of effectiveness. In the end, each method included in the combination takes account of a certain part of the pollution present indoors. The size of one part directly affects the size of the remaining parts. To put it differently, the application of one method reduces the appeal of another.

2.3 PHOTOCATALYSIS

2.3.1 DEPICTION

Photocatalysis is an air-cleaning method that is able to control indoor air pollution. It degrades several contaminants into less noxious substances (like water and carbon dioxide) whereas many other technologies only transfer them into another phase. Semiconductors are used as catalysts to oxidize VOCs at room temperature under the influence of (near-) UV light (Maira et al., 2001; Shon et al., 2008; Kim et al., 2008; Mo, Zhang, Xu, Lamson, & Zhao, 2009).

What happens is the following. A valence band (VB) that contains electrons is irradiated by UV light (photoirradiation). Photons having an energy level (excitation energy) higher than the one of the gap between the VB and the next band, the conduction band (CB), excite electrons present in the VB. These electrons then jump onto a vacant CB, leaving positive holes in the VB. Next, the electrons drive reduction whereas positive holes drive oxidation of compounds which are absorbed on the surface of a photocatalyst. The hydroxyl radical which is derived from the oxidation process, acts as the dominant strong oxidant and helps to destruct organic compounds. The final products of organic compound oxidation are water and carbon dioxide (Birnie et al., 2006; Shon et al., 2008; Ohtani, 2008).

Semiconducting materials play the leading part in the photocatalytic process. Several different types of semiconductors (pure and doped) have been tested to serve as photocatalysts. Some examples include: TiO_2, zinc oxide, cadmium sulfide, tungsten tri-oxide and zinc sulfide. Of all possible semiconductors, TiO_2 is definitely one of the most popular ones. Besides its use as a photocatalyst, TiO_2 has even proven to be of great use in several other applications like paint, plastic, UV protection, food, toothpaste… TiO_2 clearly has an expansive field of application. Its performance in photocatalytic oxidation applications is almost ideal. That is why this specific semiconductor is considered the most suitable candidate and is the most widely used. TiO_2 owes its popularity to several factors: its low cost, simple production procedure, commercial availability, non-toxicity, high chemical and thermal stability, outstanding optical and electronic properties and relatively effective activity (Maira et al., 2001; Hoffmann, Martin, Choi, & Bahnemann, 1995; Birnie et al., 2006; Shon et al., 2008; Kim et al., 2008; Mo et al., 2009; Tompkins & Anderson, 2001).

Approximately 0.62 % of the earth crust consists of titanium which makes it the ninth most copious element present. This obviously affects the commercial availability of TiO_2. Ilmenite, mineral rutile and brookite are naturally occurring titanium ores with different characteristics like their state of appearance, included impurities and TiO_2 content. The enclosed TiO_2 can be found in either one of three crystalline forms: anatase, rutile and brookite. Anatase is more suited for photocatalytic purposes than the other two phases. It also is the most active form of the triplet and the easiest one to produce. As already mentioned, the band gap of the semiconductor, which is an electronic property, plays an especially important role. Anatase experiences the highest band gap (3.2 eV) when being compared to rutile (3.0 eV) and brookite. Nowadays, anatase is most often used in commercial photocatalytic oxidation processes (Birnie et al., 2006; Shon et al., 2008). Often, anatase is combined with some rutile (Birnie et al., 2006).

In spite of all the desirable properties of TiO_2, there is also a downside to this semiconductor. In consequence of its high band width (3.2-3.0 eV), pure TiO_2 can only work as a photocatalyst when being exposed to UV light or light having even smaller radiation wavelengths (so, UVA (320-388 nm), UVB (280-320 nm), UVC (100-280 nm) and smaller). Activation cannot be expected as a result of visible light. When comprehending that the solar spectrum is only for about 5 % made up of UV light (compared with 45 % of visible light), the size of this limitation becomes incontestable (Birnie et al., 2006; Yang et al., 2007; Tompkins & Anderson, 2001). Obviously, this limitation entails a few disadvantages. Firstly, an external energy source is needed to provide UV light. Furthermore, because of the potential harm to health caused by UV light, the space in which the photocatalytic process takes place has to be closed and protected (Shon et al., 2008). Automatically it can be concluded that an extension of the usable wavelength range is needed to make photocatalytic oxidation more attractive (Ohtani, 2008). Several ways to prepare a photocatalyst responsive to visible light are possible. One method to modify TiO_2 to enhance its visible light responsiveness is by doping the TiO_2 with other substances. This doping process can be accomplished using different techniques such as: the sol-gel method, mechanical alloying, the hydrothermal method, flame spray pyrolysis, ion implantation,… Several noble (gold, silver and platinum), transition (cobalt, chromium, copper, iron, manganese, nickel and vanadium) and non-metals (carbon, nitrogen, phosphorus and sulfer) can serve as dopants. Besides doping, several other methods have been investigated to be able to extend the photocatalytic activity of TiO_2 into the visible spectrum (Shon et al., 2008; Mo et al., 2009).

2.3.2 TECHNOLOGY UNDER INVESTIGATION

This thesis focuses on cleaning indoor air from a specific gaseous pollutant by means of photocatalysis. TiO_2 is used as the semiconductor catalyst that is activated under the influence of UV light to degrade acetaldehyde, a type of VOC, into water and carbon dioxide.

2.4 DIRECT AND INDIRECT COMPETITORS

As mentioned earlier, different combinations of the three methods to reduce indoor air pollution (source control, ventilation, air-cleaning control) can be made to reach a sufficient level of indoor air quality. As a result, the degree to which the first two methods (source control and ventilation) are applied affects the demand for air-cleaning products. When, for example, new regulations take effect, demanding building materials to meet more stringent criterions, the source control method will be exploited more, leaving less room for improvement by using one or both of the remaining methods. Another example could be the situation in which all options to control the sources of pollution are already exhausted and ventilation is not applicable because of contaminants in the outdoor air. In this case air cleaning will need to act as the necessary solution (Environmental Protection Agency, 2009). So, the degree of application of source control and ventilation indirectly affects the size of the market left exclusively for air-cleaning technologies. (The overall size of the market, on the other hand, can change too due to several factors such as demographical changes.)

As to air-cleaning devices, different types exist. They all have the same or a similar objective being the cleansing of indoor air by removing polluting substances present. Photocatalytic oxidation is only one type of technology in this category next to several others. Not only products commercially available in this instant, but also future developments belong to this category. Economically speaking, all these technologies are playing on the same market and are alternative options capable of cleansing polluted indoor air. They are all competitive technologies struggling for a share of the same market.

Following this approach, all steps towards source control together with all ventilation systems act as indirect competitors when the indoor acetaldehyde concentration is influenced. Moreover, all alternative air-cleaning products (aiming at degrading acetaldehyde) different from the photocatalyst under investigation, can be denominated as direct competitors. The term ‘substitute’ can even be expected appropriate in this case since an increase in price of such an alternative product is likely to cause an increase in the quantity demanded for the air-cleaning technology under investigation. (Once again, this supposition can be checked empirically by means of the cross elasticity of demand.)

2.4.1 DIRECT COMPETITORS

Air-cleaning technologies can be divided in different groups based on various features. Firstly, two types of air-cleaning devices can be distinguished based on the area in which they operate. On the one hand, there are systems that need to be installed in the ductwork of the central heating, ventilating and air-conditioning (HVAC) system present in a building. These aim at cleansing the air in the entire building. On the other hand, portable air cleaners exist that are designed to clean the air in specific areas. These stand-alone units operate locally and continuously (Environmental Protection Agency, 2009).

Secondly, all air-cleaning devices (portable or not) can also be divided into two groups based on the type of polluting compound they need to remove or destroy, namely particulate matter or gaseous pollutants. On the one hand, there is particulate matter, composed of microscopic solids, liquid droplets, or a mixture of both suspended in the air. It can be removed by means of mechanical or electronic air filters. Mechanical air filters use filter materials, whereas their electronic counterparts operate through a process called ‘electrostatic attraction’ to capture particles. Gaseous pollutants, on the other hand, enclose combustion gases, but also organic chemicals not attached to particles. These gases and odors can be removed by gas-phase filters through physical or chemical processes. These filters use a sorbent designed to reduce one or several gaseous pollutants present at low concentrations in the indoor air that passes through them. They cannot remove all such pollutants, only the ones they were directed at during the design stage of the filter. Photocatalytic oxidation, the focal point of this work, is another technology aiming at the destruction of gaseous pollutants. As has been described before, pollutants are degraded into less harmful substances by means of a catalyst that operates under the influence of UV light. This division based on the type of pollutant addressed is not perfect as an ozone generator is a system that belongs to both groups; it addresses both particulate matter and gaseous pollutants. It applies UV light coming from lamps or electrical discharges (corona discharges) to create ozone. Ozone can react with chemical and biological pollutants to transform them into non-polluting substances (Lorimier, Le Coq, Subrenat, & Le Cloirec, 2008; Environmental Protection Agency, 2009). A more detailed description of the alternatives of photocatalytic oxidation will be given later.

The partition of air-cleaning devices based on the type of polluting compound to remove or destroy comes in handy here. The photocatalyst under investigation is aimed at controlling the acetaldehyde concentration in indoor air. So, all gas-phase filters, ozone generators or even other types of photocatalysts that are also able of reducing this concentration serve as direct competitors.

Treating particles and VOCs (gaseous pollutants) simultaneously by combining filter materials of particle filters and sorbents of gas-phase filters into one device remains a technological challenge. The difficulty here is the difference in sizes of the pollutants that need to be captured, particles being larger than VOCs. This size difference leads to the use of very different mechanisms for both types of airborne pollutants. Most joined devices simply consist of both mechanisms in series. Although being an efficient solution, the device occupies a large volume and experiences a pressure drop. Therefore, other arrangements have been and are being tested, but none of them has proven to operate under realistic conditions so far. Thus, an integrated medium of this type cannot be denominated as a possible direct competitor for now. Of course, this situation could change rather suddenly due to certain developments (Lorimier et al., 2008).

To be able to determine the market potential of the photocatalyst under investigation, it is important to compare its performance with that of its direct competitors. Although photocatalysis in general presents a very promising method to clean polluted indoor air, this method also has its flaws. The process which is applied by photocatalytic oxidation cleaners is complex and is relatively costly because of the required intensity of the UV light. Furthermore, a considerable amount of power is consumed. The need to remove multiple contaminated substances from the indoor air is difficult to fulfil. Photocatalytic oxidation cleaners are not able to destroy gaseous pollutants in indoor air completely. On some occasions, photocatalytic oxidation produces by-products that contaminate the indoor air. At other occasions, pollutants are not destroyed entirely, leading to the production of new indoor pollutants that cause adverse health effects. Additional research on performance characteristics is needed to be able to advance photocatalysis as an effective air-cleaning technology (Environmental Protection Agency, 2009). Comprehending that the rather new photocatalytic oxidation technique still has its limitations, makes it possible to see the potential provided by its direct alternatives. This is needed to assess the market potential of the photocatalyst under investigation.

2.4.1.1 Gas-phase filters

A gas-phase filter has already been mentioned as a direct alternative. Indoor air containing these gaseous pollutants passes through this filter. A sorbent is designed to reduce one or several specific types of these gaseous pollutants present at low concentrations in that flow of air. The filter can only address one or a few of these pollutants. They cannot remove them all. Several factors affect the performance of a sorbent filter: the airflow rate and velocity through the sorbent, the concentration of the pollutants being addressed, the presence of other gaseous pollutants, the total available surface area of the sorbent, physical and chemical features of the pollutants as well as of the sorbent, the pressure drop, the removal efficiency and capacity and the gas stream’s temperature and relative humidity (Environmental Protection Agency, 2009).

The removal of the addressed pollutants can occur by means of either physical or chemical processes. The process called adsorption on the one hand, operates through adsorbents which physically attract certain types of gas or vapor molecules while others are left unbroached. A regularly used adsorbent used is activated carbon. It is capable of removing many aldehydes (inter alia) except those with a low molecular weight. An important feature of adsorbents is their regular need of maintenance because of their limited capacities. Furthermore, adsorption occurs more readily at lower temperatures and humidity. Solid sorbents are often used because of their large internal surface area, stability and low cost (Environmental Protection Agency, 2009). Chemisorption, on the other hand, is a process in which gas or vapor molecules chemically react either with the sorbent material or with reactive agents impregnated into the sorbent. Like adsorption, chemisorption only addresses certain reactive pollutants (Environmental Protection Agency, 2009).

The gas-phase filter is not used that frequently. Many reasons contribute to this statement. First of all, this type of filtration system can be too big to be integrated in an average HVAC system or stand-alone unit. Next, its useful lifetime is rather limited. Once it has reached the end of its lifetime, a sorbent needs to be replaced. This is especially important because of the concern that saturated filters can release pollutants that were trapped back into the indoor air. Furthermore, its operation exclusively directed at one or a few gaseous pollutants certainly limits its field of application. Its disappointing price is a fourth downside. Finally, installation and operation costs does not work to its advantage either (Environmental Protection Agency, 2009).

2.4.1.2 Ozone generators

Ozone generators apply UV light from lamps or electrical discharges to create ozone. Ozone can react with chemical and biological pollutants to transform them into non-polluting substances. Nevertheless, one should be cautious about other possible effects ozone can have. It is an irritant gas that can lead to several adverse health effects. When reacting with chemical pollutants, harmful spin-offs can be generated. Furthermore, research suggests that ozone can only be effective in controlling indoor air quality at concentrations above public health standards. These high concentrations can even be reached when consumers meticulously stick to the instructions provided by the manufacturer (Environmental Protection Agency, 2009).

2.4.1.3 Link to demand function

Both substitutes can now be taken into account to formulate the demand function for the photocatalyst under investigation. This brings the following mathematical equation.

$$\mathrm{q}_{\mathrm{PAI}}^{\mathrm{d}} = \mathrm{D}(\mathrm{p}_{\mathrm{PAI}}, \mathrm{p}_{\mathrm{GF}}, \mathrm{p}_{\mathrm{OG}}, \mathrm{Y}, \mathrm{S})$$

The quantity demanded of p̲hotocatalysts capable of reducing the presence of a̲cetaldehyde in i̲ndoor environments is represented by $\mathrm{q}_{\mathrm{PAI}}^{\mathrm{d}}$. As could be expected, $\mathrm{q}_{\mathrm{PAI}}^{\mathrm{d}}$ is dependent upon its own price $\mathrm{p}_{\mathrm{PAI}}$. The formula further shows that the prices of both substitutes, being Gas-phase Filters (p_{GF}) and Ozone Generators (p_{OG}), also determine $\mathrm{q}_{\mathrm{PAI}}^{\mathrm{d}}$.

When the price of the technology under investigation changes, this graphically results in a shift along the demand curve whereas a change in the price of a substitutes will cause the curve to move out of its original position. It is assumed that there are no complementary products. The remaining independent variables Y and S will be dealt with later.

2.4.2 INDIRECT COMPETITORS

As was mentioned earlier, all steps taken to control the sources of acetaldehyde in indoor environments as well as all attempts made to ventilate these surroundings to lower the concentration of this specific VOC are likely to result in air of an improved quality containing less acetaldehyde. The more one focuses on these methods, the less room for improvement is left to be achieved by means of the technology under investigation. So, it is interesting to know which factors determine the attraction of both source control as well as ventilation to reduce acetaldehyde in indoor air.

2.4.2.1 Source control

2.4.2.1.1 At the initiative of a regulatory authority

2.4.2.1.1.1 Indoor pollutant levels

Europe

Regulation is an important driver in controlling the release of acetaldehyde sources indoors. Since no harmonized criteria with respect to indoor air quality exists in Europe, member states outline their own (Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, 2009). It is however important to notice that indoor air quality is a 'hot topic' and regulative steps can certainly be expected. On 11 June 2004 the Flemish Government formulated an order (Binnenmilieubesluit) which contains measures to fight health risks due to a polluted indoor environment. For several chemical, physical and biotical factors reference and/or limiting values have been determined. Reference values represent quality levels that people should try to preserve. When a reference value is exceeded in a public building, recommendations will be made to limit or eliminate the health risks. The supervisor of the building is instructed to tackle these health risks. He is also burdened with this task when the indoor environment of a public building poses a threat to health. Limiting values, on the other hand, represent maximally permissible risk levels. These levels are not to be exceeded (except in cases of supremacy). If they are, preventive actions have to be taken. When a limiting value in a residence is exceeded or when its indoor environment poses a threat to health, this residence is found uninhabitable. For acetaldehyde, that belongs to the category of chemical factors like all other VOCs, a reference value, being ≤ 4600 µg/m^3, has been determined. The reference value for all VOCs is ≤ 200 µg/m^3. In neither case, limiting values are mentioned.

Although the focus of this thesis is on non industrial environments, it is also highly interesting to consider regulations relevant in industrial settings. The European Directive (98/24/EG) on the protection of the health and safety of workers from the risks related to chemical agents at work was converted in Belgium into the Royal Decree of 11 March 2002. According to this decree, employers are to evaluate the threats to the safety and health of the employees posed by the presence of chemical agents at work and should take the necessary preventive measures. Annex I of this decree contains limit values which are not to be exceeded. The limit value for acetaldehyde is expressed as an 8-hour Time Weighted Average (TWA) and amounts to 25 ppm (ml/m^3) (independent of temperature and atmospheric pressure) or to 46 mg/m^3 at a temperature of 20 °C and a pressure of 101,3 kPa.

United states

In the United States (US), as to its indoor definition (which is different from the one used outdoors as will be clarified later), VOCs are organic chemical compounds found indoor which are capable of volatizing under normal indoor atmospheric conditions (temperature and pressure). The presence of these types of organic chemical compounds in non-industrial settings is not regulated, except for formaldehyde, which is treated as a carcinogen by the Occupational Safety & Health Administration [OSHA]. On the other hand, the Environmental Protection Agency [EPA] (which mission is to attempt to protect human health and the environment) does try to raise awareness concerning the variety of possible health effects caused by VOCs present in indoor environments. Sources of VOCs are listed as well as ways to reduce indoor exposure. Some steps to take are: an improved ventilation, an adaptation of the buying behavior, a limitation of exposure to the emissions of certain substances… Rationally, it would seem like a good idea to consult the labels and certificates of bought products to check for their VOC content or emission potential or anything like that. Unfortunately, this is not the most advisable thing to do. The norms and requirements currently used within the product labeling and certification industry for indoor products are not standardized. Prescriptions to craft consistent, protective standard test methods to rate and compare products as well as materials are still to be determined by the government or a third-party organization.

Remarkably, the presence of certain substances in industrial settings has been regulated by the OSHA. Its Occupational Safety and Health Standards, for example, deals, inter alia, with toxic and hazardous substances. These substances are chemicals present in the workplace (including shipyards) that are capable of causing harm. An employee's exposure to acetaldehyde, which is an air contaminant, is not to exceed its 8-hour TWA during any 8-hour shift of a 40-hour workweek. This TWA was determined from breathing-zone air samples and amounts to 200 ppm (at 25 °C and 760 torr) or approximately 360 mg/m^3.

2.4.2.1.1.2 Building materials, products and human activities

As mentioned before, by carefully selecting the building materials during the design stage of a building and the products used in day-to-day life, one can try to control acetaldehyde sources. A similar effect can be obtained by paying attention to the activities one performs, e.g. smoking, using combustion appliances… The extent to which certain products release contaminants (like VOCs) could be regulated in different ways, e.g. by formulating emission limitations for products, by regulating their composition, by defining labeling prescriptions…

Europe

Currently, in Europe, such regulation only exists to a limited extent but this is definitely bound to change. An example of a directive that includes product norms is the Paint Products Directive (2004/42/EC). This directive aims at limiting the total VOCs content in certain paints and varnishes as well as in vehicle refinishing products to prevent or reduce air pollution which results from the contribution of VOCs to the formation of tropospheric ozone. Therefore, the technical specifications of these type of products (listed in Annex I) are approximated. Clearly, this directive explicitly deals with the composition of paint products.

Another example is the Construction Products Directive (89/106/EEC) which aims to enable free movement of all construction products within the European Union [EU]. This type of products includes all products produced to be permanently incorporated in construction works. For this cause a common technical language is generated which comprises harmonized standards as well as European technical approvals. This enables manufacturers to communicate the performance of their product with regard to a number of characteristics which affect the basic requisites of construction works. These requisites (listed in Annex I) are connected with topics like mechanical strength and stability, safety in case of fire, hygiene, health and the environment, safety in use, protection against noise and energy economy and heat retention and may influence the technical characteristics of a product. The hygiene, health and the environment requirement is probably most relevant in this case. Construction works must be designed and built while keeping in mind the hygiene or health of the occupants and the neighbors. The giving-off of toxic gas and the presence of dangerous gases in the air are mentioned explicitly because of the possible threat these incidents pose to the hygiene and health of the individuals mentioned above.

Both the Paint Products Directive (2004/42/EC) and the Construction Products Directive (89/106/EEC) are clear examples (others were certainly possible) of existing legislative acts with regard to product norms drawn up by the EU. Of course, to ensure the enforcement of these acts, directives are to be implemented by each member state. Each such state can decide independently on the way it shall attempt to attain the objective put forward in the directives.

The following example relates to the Belgian regulation. The law of 21 December 1998 concerning Product Norms (Productnormenwet) aims at improving sustainable consumption and production and protecting the environment and public health. It obliges producers to design their products with a certain degree of care and prevention. A producer, for example, must inspect all environmental effects of its products that could be observed in the course of their entire life cycle. The negative ones should be prevented (Vlaamse Overheid Departement Leefmilieu, Natuur en Energie, 2009).

United States

In the US, some clear examples of regulatory product standardisation in view of hampering the adverse health effects caused by releases of contaminants polluting indoor air can also be found. Such an example is the Consumer Product Safety Improvement Act of 2008 which attempts to ameliorate the safety of consumers with special attention to children’s products. According to this act, to manufacture or export toys to the US one must be able to hand over a general certificate of conformity which is based on testing.

California Proposition 65, also known as the Safe Drinking Water and Toxic Enforcement Act, was implemented in 1986 and was drafted at the initiative of voters. It required a list of chemicals known to cause cancer or reproductive harm to be drawn up. Firms are not to deliberately discharge these chemicals when the risk exists that these substances can reach drinking water sources. They are also obliged to warn Californians when they are aware that these individuals are being exposed to listed substances. This act is also used as a reference for carcinogenic compounds in other fields than water safety, for example in Section 01350 concerning VOC emissions from products into indoor air.

2.4.2.1.1.3 Pollutants tracked from outdoors

As mentioned earlier, pollutants like acetaldehyde can also be tracked from outdoors. Therefore, this paragraph deals with the regulation of outdoor air. Because this topic deviates to a certain extent from the main subject of this thesis, being indoor air pollution, this discussion will be kept reasonably brief.

Europe

The European Solvents Emission Directive (1999/13/EC), one possible example of relevant regulation, of the European Commission aims at limiting the emissions of VOCs caused by the use of organic solvents in certain activities and installations. The directive lists the activities to which it applies. Every activity is accompanied by a solvent consumption threshold. When a listed activity exceeds its accompanying threshold, it falls within the scope of the directive and measures and procedures are provided that need to be implemented. The eventual purpose of the directive is to prevent or reduce the direct and indirect effects of emissions of VOCs into the environment (mainly into the air) and the potential risks to human health.

Another example is the National Emission Ceilings Directive (2001/81/EC) which provides national emission ceilings for certain atmospheric pollutants. By establishing these ceilings exposed to successive reviews, this directive aims at limiting emissions of acidifying and eutrophying pollutants and ozone precursors to improve the protection in the community of the environment and human health against risks posed by adverse effects from acidification, soil eutrophication and ground-level ozone. Furthermore, it hopes to move towards long-term objectives to not exceed critical levels and loads and to effectively protect all people against recognised health risks from air pollution. The years 2010 and 2020 are taken as benchmarks. By 2010, national emissions of different pollutants (including VOCs) of each member state of the EU were not to be higher than the emission ceiling accompanying that specific pollutant (taking into account certain modifications made by Community measures). Thereafter, the ceiling should evidently always be respected. Member states are also supposed to specify their planned procedure to reach these ceilings in a reduction programme.

The national emission ceiling of Belgium for VOCs, that needed to be attained ultimately in 2010, amounts to 139 kt. The original ones proposed by the European Commission were tighter. Referring to this proposal, more achievable ceilings were suggested based on consultations with relevant sectors, available information and inquiries in adjacent countries and this in each district. After some negotiations with the European Commission the following VOC emission ceilings were determined: 70.9 kt for Flanders, 28 for the Walloon provinces, 4 for Brussels and the remaining 35.6 for all non-stationary sources in Belgium, totaling approximately 139 kt. Federal (product standards) as well as regional (mobility policy) measures can be taken to attain the ceiling for non-stationary sources (Vlaamse Overheid Departement Leefmilieu, Natuur en Energie, 2006).

At the federal level, no specific measures were taken to reduce the emission of VOCs. As to non-stationary sources, Belgium has foreseen to influence the evolution of mobility and stimulate environmental friendly vehicles and fuels. As to its stationary counterpart, several steps have been taken to limit the emissions of heating appliances. The measures proposed in Flanders were based on an extensive study programme. The programme distinguished between several major industrial sectors for which emissions, possible measures and reduction potential were determined. To establish these measures, the sectors were of course consulted. Sectoral conditions in the Vlaams reglement betreffende de milieuvergunning (Vlarem) (the Flemish regulation concerning the environmental permit which will be covered in more detail later) and environmental permits in individual companies will be applied to impose the measures. For VOCs in particular, Vlarem conditions for storage and handling, vehicle refinishing, phase II vapour recovery, car assembly… were already adopted and in, inter alia, the chemical industry and production of paints and inks, company specific measures have been proposed. To reduce the emissions of atmospheric pollutants in the Walloon provinces, the Large Combustion Plants Directive (2001/80/EC) (which aims at limiting sulphur dioxide, nitrogen oxides and dust emissions released from certain combustions plants) and Integrated Pollution Prevention and Control Directive (2008/1/EC) (which will be covered later) are to be implemented. For VOCs in particular, the implementation of the Solvents Emission Directive (1999/13/EG) and the Integrated Pollution Prevention and Control Directive will lead to emission reductions. The implementation of the European Solvents Emission Directive (1999/13/EG) and Paint Products Directive (2004/42/EG) resulted in emission reductions for VOCs in Brussels. Furthermore, awareness raising campaigns are conducted to reduce the application of solvent containing products (Vlaamse Overheid Departement Leefmilieu, Natuur en Energie, 2006).

By combining all federal and regional measures, emission projections can be made. When considering all measures that have already been taken or will certainly be taken, Belgium was projected to emit 129.2 kt of VOCs in 2010. Additional measures could even result in a total emission of 121.9 kt. Both projections are clearly lower than the emission ceiling of 139 kt of VOCs (Vlaamse Overheid Departement Leefmilieu, Natuur en Energie, 2006).

In 2008, a state of affairs for Flanders was published. The prognosis for 2010 of the VOCs emissions produced by non-stationary sources still applies. For stationary sources, on the other hand, the projection was slightly raised because of a more accurate list of emission sources and an unexpected growth of emissions in several sectors. Nevertheless, this projection still does not exceed the established emission ceiling (Vlaamse Overheid Departement Leefmilieu, Natuur en Energie, 2008).

As mentioned before, the Vlarem (Vlaams reglement betreffende de milieuvergunning) regulation is a relevant means to an end in guiding Flemish companies toward more environmentally friendly practices (especially in terms of an abatement of acetaldehyde emissions). In general, the Vlarem I and Vlarem II regulation applicable in Flanders fights environmental pollution caused by troublesome installations. Annex 1 of Vlarem I lists all such installations, whereas Vlarem II (Part V) contains binding sectoral environmental conditions for each of the listed installations. To point out the relevance of this regulation, an example is given.

Section 5.30.1 of Vlarem II contains all relevant regulation with regard to installations for the production of ceramic products. It starts by mentioning which types installations listed in Annex 1 of Vlarem I belong to this group (article 5.30.1.1). Then, article 5.30.1.2 refers to distance rules which deal with the location of the installations. Next, article 5.30.1.3 contains two provisions with regard to air pollution, one about the oxygen reference level (1°) and another about emissions (2°).

The second provision mentions three interesting topics. Firstly, it is pointed out that process integrated measures are to be taken before implementing best available techniques (BAT) for flue gas cleaning which carries out the message that prevention is better than cure. The designation ‘BAT’ comes from the Integrated Pollution Prevention and Control Directive (2008/1/EC). This directive aims at preventing and controlling pollution coming from industrial and agricultural activities with a high pollution potential performed in the EU. Operators performing these activities (listed in Annex I) are required to have an environmental permit from the authorities in the EU countries. To obtain this permit, certain environmental conditions based on BAT have to be met, so that the companies themselves are responsible for the prevention and reduction of any pollution they cause. The definition of BAT is given in article 2 of the Integrated Pollution Prevention and Control Directive:

> ‘best available techniques’ means the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole:
>
> (a) ‘techniques’ shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned;
>
> (b) ‘available techniques’ means those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator;
>
> (c) ‘best’ means most effective in achieving a high general level of protection of the environment as a whole. (p. 4)

The European commission simplifies the exchange of information concerning BAT between several member states of the EU by having the Integrated Pollution Prevention and Control office in the Spanish city Sevilla draft BAT reference documents (BREFs). The office gets help from the member states and the industries involved. The documents can be consulted in book form or via the internet.

In Flanders, a BAT centre is responsible for the gathering, processing and spreading of information concerning environmentally friendly techniques. In cooperation with the department of environmental and process technology of the Vlaamse instelling voor technologisch onderzoek [VITO] (which is the Flemish institute for technological research), this competence centre has created a guide consisting of several fact sheets about air emission abatement techniques applicable to cleanse industrial waste gases and a decision support system (LUSS) to select those techniques capable of addressing a certain waste gas problem (Vlaamse Instelling voor Technologisch Onderzoek, 2004). Literature (including LUSS and BREFs), surveys with Dutch suppliers and interviews with suppliers, companies and the competent authority were taken into account when drawing up renewed fact sheets. These fact sheets on air emission abatement techniques are the Dutch and Flemish input in the revision of the BREF Wastewater and gas treatment for the chemical industry, while its field of application is broader than just the chemical industry. When exploring the fact sheets one will notice that several of the presented techniques are indicated as being capable of removing VOCs (whether intended or unintended). Clearly, photocatalytic oxidation, the technology under investigation, will have to compete directly with many other technologies like cryocondensation, several types of adsorption (e.g. active coal, zeolites…) and absorption (e.g. acid gas scrubber, alkaline gas scrubber…), all presented techniques based on biological cleaning and thermal oxidation… The fact sheets also provide a very useful overview which enables a preliminary comparison of the listed techniques (Vlaamse Instelling voor Technologisch Onderzoek & Infomil, 2009).

Secondly, the second provision of section 5.30.1 of Vlarem II contains emission limit values for flue gases coming from heating installations. These values differ from the general limit values which can be found in section 4.4.3 of Vlarem II and which exist for several parameters like for different types of VOCs. For acetaldehyde emissions, for example, this limit amounts to 20 mg/Nm^3 (with a mass flow rate of 100 g/h). In section 5.30.1, an irregular limit value for all VOCs (contrary to for each VOC separately) is included.

Thirdly, the second provision also determines which method is to be applied to measure the concentration of the parameters coming from heating installations.

United states

In the US, the EPA aims at protecting and improving the air quality and the stratospheric ozone layer. This responsibility was enacted in the Clean Air Act. The EPA sets National Ambient Air Quality Standards (NAAQS) concerning pollutants which can harm public health and the environment. Primary standards are set to protect public health, whereas secondary standards aim at protecting public welfare.

For 6 major pollutants (criteria pollutants), NAAQS were set by the EPA Office of Air Quality Planning and Standards [OAQPS]. One such pollutant is ozone, which can be created at ground-level by a chemical reaction between oxygen molecules and VOCs under the influence of sunlight. Depending on its location in the atmosphere, ozone can be harmful or not. Ground-level ozone, which is the primary constituent of smog, is considered bad.

A logical conclusion could be that because the presence of ozone is limited by law, this indirectly affects the emissions of VOCs (which should be kept low to prevent the creation of ozone). Unfortunately the EPA has caused confusion concerning the term 'VOC', namely it has a different meaning indoor compared to outdoor. People exposed to VOCs indoor, can potentially expect adverse health effects. Of course, this is also the case outdoors. Nevertheless, EPA is mainly concerned about VOCs because they are able to react with carbon monoxide or nitrogen oxides to create ground-level ozone which can lead to photochemical smog. However, not all VOCs have a similar ability to react. Some do not or only to a limited extent and are therefore exempted from the definition of VOCs EPA uses in its regulation for outdoor air. This definition, which only includes VOCs expected to cause photochemical smog, is not applicable indoor.

But is acetaldehyde included in the outdoor definition of VOCs and is it thus regarded as capable of creating ozone? When this is not the case, the NAAQS concerning ozone are not to be considered further in this thesis. The Chemical Summary for Acetaldehyde (Environmental Protection Agency, 1994) mentions that acetaldehyde can indeed contribute to the formation of photochemical smog in the presence of other VOCs. So, the NAAQS concerning ozone do indeed indirectly affect the emissions of VOCs.

An important remark to make is the fact that the previous general overview of regulation (affecting the extent to which one attempts to reduce indoor air pollution by controlling contaminating sources) obviously only presents a limited amount of all existing regulation. Attention has been paid, however, to the selection of the regulative documents. The collection of examples given comprises noteworthy regulation. Furthermore, be sure to note that each regulative document presented earlier is relevant to this thesis to a different extent (i.e. specifically with regard to acetaldehyde or rather general).

2.4.2.1.2 At the initiative of manufacturers

Manufacturers themselves could start paying more attention to the fact that their products act as sources of air pollution. In fact, this could be a way for them to distinguish their products from competing ones. This seems a reasonable initiative since people are increasingly aware of the regretful air quality found indoors. Furthermore, manufacturers could also start taking steps bearing in mind the health effects caused by their products because competitors do so and lagging behind is not a very tempting option.

To communicate the efforts a manufacturer has taken, e.g. to improve indoor air quality, he can choose to certify its product (although the value of such certificates is sometimes questioned as mentioned above). By simply inspecting the internet, one can easily find an abundance of certificates. Greenguard, Eurofins, Scientific Certification Systems (SCS), the Carpet and Rug Institut (CRI)… are only a few organizations providing certificates to prove the effort a manufacturer has put in to controlling the emissions of their products. The EU has also created a label, called the Ecolabel, which enables firms to communicate that their products or services are more eco-friendly. The corresponding regulatory framework can be found in Directive 880/92/EEG. When an offer meets all requirements of this directive it can carry the Ecolabel logo, which is a flower.

Although many certificates are possible, manufacturer should not randomly choose one because important differences exist between them. Some certificates, for example, are handed over after a thorough assessment by an independent, third party organization which is qualified and licensed, while with others a third party is only needed to validate. Evidently, other differences between existing certificates can be expected. Obviously, a manufacturer should try to acquire a certificate which reflects all efforts taken.

As mentioned, due to raised awareness concerning indoor air quality, further steps to control the sources of indoor air pollution (whether forced or voluntary) can be expected which implies less room left for improvement through means of ventilation or air-cleaning technologies.

2.4.2.2 Ventilation

2.4.2.2.1 Europe

In 2002 the European Energy Performance of Buildings Directive (2002/91/EC) came into force. This directive aims at improving the energy performance of both existing and new buildings within the EU taking into account certain minimum requirements. All member states must also ensure the certification of their energy performance and must regularly inspect the air-conditioning systems and boilers present in their buildings. In general, the Energy Performance of Buildings Directive only affects the residential sector and the tertiary sector (Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, 2009).

In Flanders, as of January 2006, one has to comply with the energy performance regulation (Energieprestatie en Binnenklimaat) when planning to build or rebuild a residence. When a licence from the urban design department is requested for a certain building, this building is to attain a specified level of thermal insulation (K-rate) and energy performance (E-rate) to limit the consumption of energy. The E-rate depends, inter alia, on the degree of ventilation. The lower this rate, the more economical the building is with regard to its energy consumption. Regularly, this requisite is severized. As of January 2010 this E-rate can at the utmost amount to E80, whereas previously an E-rate up to E100 was allowed. However, this derating only applies to residences. Schools and offices can still stick to an E-rate of E100. The compliance to both the K-rate and the E-rate improves the general comfort of the buildings. Furthermore, each new building should be ventilated to a certain extent and in a controlled manner to ensure the indoor air quality and a healthy living environment (Vlaams Energieagentschap, 2010). The Flemish Energy Performance regulations takes the Belgian NBN D50-001 norm of 1991 into account. This norm concerning the procurement of ventilation in residences identifies how residences should best be equipped to enable a correct ventilation of the different chambers. Whether the building will indeed be ventilated depends on the user and his way of managing the procurements (Wetenschappelijk en technisch centrum voor het bouwbedrijf, 1999).

2.4.2.2.2 United States

In the US the American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE] has formulated a standard, being ASHRAE Standard 62, which prescribes minimum ventilation rates to obtain an indoor air quality acceptable to human occupants. The goal is to reduce the potential for adverse health effects as much as possible. All indoor or enclosed spaces that people may occupy fall within the scope of this standard unless more stringent standards or requirements are applicable. ASHRAE Standard 62 is subjected to a continuous maintenance protocol and consists of a parent document together with some approved addenda. It is important to note that the standard is voluntary. This implies that one is only obliged to comply with it when the corresponding locality or state has adopted it.

Clearly, regulation influences the extent to which one ventilates. For example, the exact height of the required E-rate, codetermines to which extent ventilation is made use of in Flanders. Thus, changes in this rate will affect the room left for improving the indoor air quality through means of air-cleaning technologies.

Once again, keep in mind that this overview of regulation was never intended to be all-embracing, nor is a certain example necessarily as relevant for this thesis as another.

2.4.3 SCHEMATIC OVERVIEW

Figure 2 represents all methods to reduce indoor air acetaldehyde pollution. The more the first two methods, being source control and ventilation, are used, the less room for improvement of the indoor air quality (by reducing the acetaldehyde presence) is left for air-cleaning technologies. In previous parts, source control and ventilation were said to compete indirectly with air-cleaning technologies. All air-cleaning technologies applied to reduce the acetaldehyde pollution in indoor air, were denominated as direct competitors of the photocatalyst under investigation.

Figure 2. Methods to reduce indoor air acetaldehyde pollution

2.5 COMPLETION OF DEMAND FUNCTION

As mentioned earlier, there are still two independent variables left in the formulated demand function which have not been dealt with. The first one is the consumer's income Y. A change in total income affects the quantity demanded of the technology that is being developed. However, the exact result of this change on the quantity demanded depends upon which type of product the photocatalyst is. When the income of consumers increases, normal goods will be bought more whereas inferior goods will be bought less because more expensive, superior products are now affordable.

To check whether or not the technology under investigation is either a normal or an inferior good, one can apply an economic concept termed the income elasticity of demand. This concept can mathematically be presented through means of the following formula.

$$\eta_{\mathrm{Y}} = \frac{\Delta\, \mathrm{q}^{\mathrm{d}}_{\mathrm{PAI}}\ (\mathrm{in}\ \%)}{\Delta\, \mathrm{Y}\ (\mathrm{in}\ \%)}$$

The income elasticity of demand (η_{Y}) represents the percentage change in the quantity demanded of the photocatalyst under investigation ($\Delta\, \mathrm{q}^{\mathrm{d}}_{\mathrm{PAI}}\ (\mathrm{in}\ \%)$) due to an increase of one percent in income ($\Delta\, \mathrm{Y}\ (\mathrm{in}\ \%)$). A positive elasticity indicates that this photocatalyst is a normal good, whereas a negative sign suggests that it is in fact an inferior good (Lipsey & Chrystal, 2004).

It is important to note that when the distribution of income changes (but total income is kept constant), meaning some people become richer whereas others become poorer, this could also affect the quantity demanded. For normal goods, this implies that the lucky individuals which gained income can now afford more while the others, which experienced an income loss, will no longer be able to buy as much as they usually did. For inferior goods, obviously, the opposite holds. If both groups of individuals (the gainers and the losers) purchase the photocatalyst in similar proportions, the changes in the distribution of income will not affect the total quantity demanded of that good whereas in the opposite situation quantity demanded will certainly be influenced (Lipsey & Chrystal, 2004).

The following sections will take a look at the evolution of total income and income distribution. Data available at the website of the European commission (European Commission, 2011) indicate that income has increased since 1996. In 2009 a recidivism in income occurred. In this year the global economy went into recession which was a direct result of a housing and financial crisis (International Labour Office, 2009). To express income inequality, the European Commission uses the S80/S20 ratio and the Gini coefficient. The first indicator compares the share of income going to the top quintile (20 %) of the population (S80) with the share going to the bottom quintile (S20). The second indicator, the Gini coefficient, is a summary measure based on the cumulative share of income accounted for by the cumulative percentages of the number of individuals. This coefficient equals 0 % when income is distributed completely equally. It amounts to 100 % in the opposite case. For both indicators a weighted average of all 27 national ratios was calculated in which each country ratio was weighted by the member state's population size. Both weighted averages remained rather unchanged between 2005 and 2008. However, some important county changes existed. For example, inequality in the ten new member states was reduced. The EU-15 data, on the contrary, show little change (European Union, 2010).

Data available at the website of the European Commission (European Commission, 2011) suggest that the Belgian income has experienced an increasing trend from 1995 up till 2008. In 2009 the Belgian income decreased a little. The Belgian Federal Public Service of Economy, S.M.E.s, Self-employed and Energy (Federale Overheidsdienst Economie, K.M.O., Middenstand en Energie, 2010) provides the evolution of the Gini coefficient which describes the income distribution on its website. These data clearly show that, since 1992, income has been distributed more and more unequally. Strangely enough, the latter finding cannot be supported based on the data presented by the European Commission. These show that the Gini coefficient remained rather constant between 2003 and 2008 indicating that income distribution did not change significantly in this period. Based on the S80/S20 ratio, the same observation could be made (European Union, 2010).

In the US, the United States Census Bureau reports on income. Based on data made available at its website, it can be concluded that income (United States Census bureau, 2010) as well as income inequality (United States Census bureau, 2010) (expressed by means of the Gini coefficient) have mainly have increased during the past decades.

The second undefined independent variable S in the formulated demand function comprises several factors that vary from individual to individual. These may include one's age, number of children, place of residence as well as other assets. Clearly, this enumeration is not all-embracing and many other factors may be relevant. One possible example relevant in this thesis is the age of one's residence. The older the building, the less gases left to be released by building materials (Rothweiler, Wäger, & Schlatter, 1992).

2.6 LESSONS LEARNED

This chapter listed all variables affecting the quantity demanded of a photocatalyst capable of reducing indoor air pollution. The competitive environment in which the technology under investigation will have to emerge was mainly emphasized. As the demand function indicates, the prices of substitutes influence the quantity demanded of the photocatalyst. The lower these prices, the more interesting the substitutes become. Two prominent substitutes have been determined, being gas-phase filters and ozone generators. Both technologies, which are based on principles quite different from photocatalysis, still have their flaws. Obviously, this creates opportunities for the technology under investigation. However, photocatalysts capable of reducing indoor air pollution are still facing some limitations as well.

Besides substitutes, indirect competitors were also pointed out. As was mentioned earlier, photocatalysts and their direct competitors belong to the category of air-cleaning technologies which are to be combined with source control and ventilation measures to reduce indoor air pollution. Source control is always the first option to consider, followed by ventilation and air-cleaning technologies. Thus, the more one of the indirect competitors is utilized, the smaller the need for air-cleaning technologies. Several motives were given that lead to the application of either source control or ventilation measures. As was stressed earlier, regulative authorities play a major role in this case. Regulation can oblige specific behavior without direct input from companies which are affected by it. Therefore, the influence of authorities should never be overlooked.

CHAPTER III: SUPPLY

3.1 THEORETICAL APPROACH

This section focuses on the supply side. The quantity supplied can be defined as the amount of a certain product companies are able and willing to offer for sale. Three variables determine the quantity supplied, namely the price of the product, the prices of production inputs and the state of technology. This can be represented mathematically by means of the following supply curve.

$$q_n^s = S(p_n, F_1, \dots, F_m)$$

The quantity supplied of a product n (q_n^s) is determined by the price of this product (p_n) and the prices of all inputs into production ($F_1, \dots, F_m$). The form of the function is determined by the state of technology (Lipsey & Chrystal, 2004).

Like the demand function, the supply function can be represented graphically (Figure 3). In this case, the quantity supplied of a certain product (q_n^s) serves as the dependent variable and the price of this product (p_n) as its independent antithesis. The other independent variables ($F_1, \dots, F_m$) (as well as the form of the function) are kept constant (the ceteris paribus assumption). Again, contrary to mathematical expectations, the independent variable is depicted on the vertical axis, whereas the dependent variable is represented on the horizontal axis.

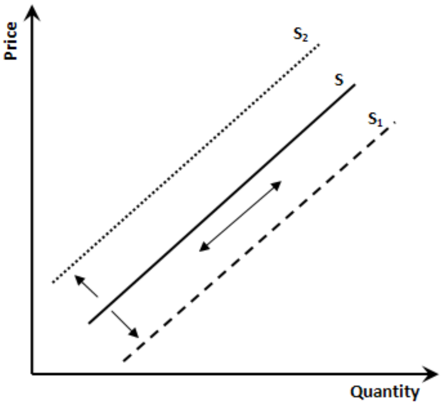

Figure 3. Supply function

Changes in the price of the product are likely to affect the quantity supplied. Graphically, this will result in a shift along the supply curve S as the double arrow depicts. Characteristic of this curve is that price increases (decreases) lead to increases (decreases) in quantity. This feature is proven by the positive slope of the function (Lipsey & Chrystal, 2004).

When, on the other hand, one of prices of the inputs used to create the outputs ($\mathrm{F}_1, \ldots, \mathrm{F}_\mathrm{m}$) changes, the supply curve S shifts into a new position. A price increase can be represented by a shift of the curve to the left (e.g. into position S_2) because less will be supplied at any given price, whereas a price reduction can be depicted by a movement of the curve to right (e.g. into position S_1) because more will be supplied at any given price. When several or all of the prices of the production inputs change, it is more difficult to foresee the exact shift of the supply curve because some changes can neutralize one another either partially or completely (Lipsey & Chrystal, 2004).

Technological changes also affect the quantity supplied of a certain good. A change that decreases production costs, for example, leads to higher profits, which in turn leads to an increased production. This can be depicted graphically by a rightward shift of the supply curve which shows that companies are willing to produce and sell more of the product at any given price than they were before the change took place (Lipsey & Chrystal, 2004). Once again, recall a perfectly competitive market is assumed.

Having approached supply from a theoretical point of view, it is time to apply it to the technology under investigation. Some questions will need to be asked. What is the price of the photocatalyst capable of reducing the presence of acetaldehyde in indoor air? Which are the inputs necessary to produce this technology and what is their price? Which technological changes can be expected?

3.2 PRODUCTION INPUTS

This section deals with the implementation of the general supply function. Besides the price of photocatalysts capable of reducing the presence of acetaldehyde in indoor environments (p_{PAI}) and the state of technology, the prices of the various production inputs ($F_1, \ldots, F_m$) are likely to affect the quantity supplied of a technology capable of reducing the acetaldehyde level in indoor air by means of photocatalysis. The most prominent ones will be determined and discussed to complete the following supply function.

$$q_{PAI}^{s} = S(p_{PAI}, F_1, \ldots, F_m)$$

3.2.1 PHOTOCATALYST

To produce a technology based on photocatalysis which is capable of reducing the acetaldehyde level in indoor air, one obviously needs photocatalytic material. The technology under investigation uses the semiconductor TiO_2. Although several types of this photocatalyst are commercially available, it can also be prepared in a laboratory. A CEA can be applied to choose between all options. Once one specific photocatalyst is selected, one should obviously watch over its price because, as the supply function points out, it affects the quantity supplied of the technology under investigation.

3.2.1.1 Cost-effectiveness analysis

3.2.1.1.1 Theoretical approach

A CEA, like a cost-benefit analysis (CBA), is a method in which all costs and benefits associated with a certain project are compared. When performing a CBA, all costs as well as benefits have to be monetized, discounted over time and netted to result in a net benefit of the project. The project is recommendable when its net benefit is positive. When analysts are either unable or unwilling to value the benefits of a project in monetary terms, CEA represents an alternative analysis method. In a CEA, all benefits of the project are first combined in one quantified effectiveness measure. By comparing the costs and the effectiveness measure (representing the benefits) of the project, a cost-effectiveness (CE) ratio can then be calculated. Several mutually exclusive projects can finally be compared based on their cost-effectiveness ratio. CEA clearly acts as an evaluative tool (Boardman, Greenberg, Vining, & Weimer, 2006).

CEA, though still used within the originally military framework, is currently being applied to evaluate projects in such areas as health and environment. This is not surprising as benefits of projects in these areas are extremely difficult to monetize (Boardman et al., 2006; Shepard & Thompson, 1979).

Two different types of cost-effectiveness ratios exist. The first one, the average cost-effectiveness ratio (ACER), represents the average cost per effect which can be expressed mathematically by means of the following formula (Compernolle, 2010; Hoch & Dewa, 2008).

$$\mathrm{CE_i} = \frac{\mathrm{C_i}}{\mathrm{E_i}}$$

with i = 1, 2, …, n

n = number of alternative projects

Obviously, out of all possible alternative projects, one should choose the one with the lowest ACER.

The second one, the incremental cost-effectiveness ratio (ICER), represents the additional cost (in a specific currency) required to obtain one unit of additional benefit (in a chosen unit different from a currency) (Cantor & Ganiats, 1999; Compernolle, 2010; Löthgren & Zethraeus, 2000). The ICER can be calculated using the following formula (Compernolle, 2010; Hoch & Dewa, 2008).

$$\mathrm{CE_{ij}} = \frac{\Delta\mathrm{C}}{\Delta\mathrm{E}} = \frac{\mathrm{C_i} - \mathrm{C_j}}{\mathrm{E_i} - \mathrm{E_j}}$$

with C = costs

E = effects

i and j = alternative projects

When the costs of project i are equal to the costs of project j, or in other words $\Delta\mathrm{C} = 0$, one should opt for the project having the highest effects. On the other hand, when $\Delta\mathrm{E} = 0$ representing effects that have been kept constant, the project having the lowest costs is advisable (Boardman et al., 2006; Compernolle, T., 2010).

The concept of cost-effectiveness can be illustrated graphically on what is called a CE plane (Figure 4). This plane is divided into four quadrants by means of on the one hand the horizontal axis representing the difference in effects in comparison with a reference standard and on the other hand the vertical axis depicting the difference in costs in comparison with this standard. The reference standard is located at the origin, while an alternative project is represented by a point on the plane with corresponding coordinates P(ΔE,ΔC). Projects situated in quadrant I experience both increased effectiveness and costs, whereas the opposite applies in quadrant III (decreased effectiveness and costs). Projects in quadrant IV are characterized by an increased effectiveness while having decreased costs. The opposite (decreased effectiveness, increased costs) applies to projects in the remaining quadrant, being quadrant II (Black, 1990; Compernolle, T., 2010).

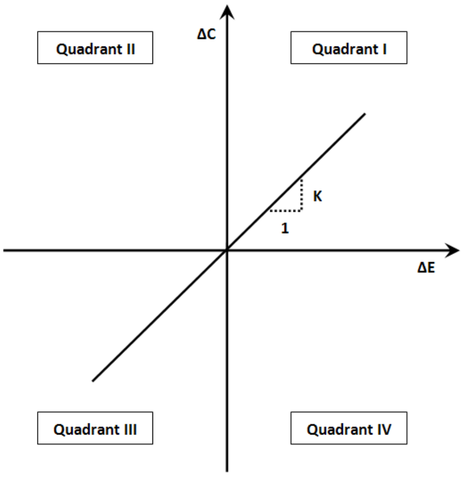

Figure 4. Cost-effectiveness plane

From The CE Plane: A graphic representation of cost-effectiveness. (p.212), by W.C. Black, 1990, *Medical Decision Making, 10,* 212-214.

The CE plane can be divided into two halves using a straight line through the origin with slope K. This constant is the maximum acceptable CE ratio or the price one is willing to pay to raise ΔE with one unit. In each point of the straight line the following equation is satisfied.

$$\mathrm{K} \times \Delta\mathrm{E} = \Delta\mathrm{C}$$

As the equation shows, the monetary difference in effects equals the difference in costs in every point of this line. To put it differently, the benefits equal the costs. Obviously, by introducing the constant K, one is actually performing a CBA.

On the one hand, all cost-effective projects are located on the right side of the line. For these projects the following inequality holds.

$$\mathrm{K} \times \Delta\mathrm{E} - \Delta\mathrm{C} > 0$$

The left side of the inequalities can be rewritten which leads to the following inequality.

$$\mathrm{NB(K)} > 0$$

Now, the left side of the inequality clearly represents the net benefit the alternative offers, in comparison with the reference standard, expressed in monetary terms.

On the other hand, all projects situated to the left of the straight line are not cost-effective. The previous inequalities will not hold in this case (Black, 1990; Compernolle, 2010; Löthgren & Zethraeus, 2000).

Thus, based on the previous, projects in quadrant IV will always be cost-effective, the ones in quadrant II however, will never be. In these quadrants, ΔE and ΔC have different signs and no trade-off is possible between both variables. However, in the remaining quadrants (I and III), ΔE and ΔC have the same signs and a trade-off between the variables can be made. In these cases, K has to be considered when evaluating the cost-effectiveness of the projects. The further one moves to the right of the line, the better the CE ratio becomes (Black, 1990; Compernolle, 2010).

3.2.1.1.2 Units of the costs and effects

To be able to perform a CEA, one has to reflect on the units which will be used to express the effects and costs.

3.2.1.1.2.1 Effects

The effectiveness is expressed in terms of conversion of acetaldehyde; the more conversion, the larger the effect. Conversion can be formulated by means of two different catalytic quantities.

Firstly, the obtained conversion percentage could be used, which describes the efficiency of the photocatalyst in degrading the pollutant, being acetaldehyde. The exact formula to calculate the conversion percentage is given below (Verbruggen, 2009).

$$\text{Conversion [\%]} = \frac{\text{pollutant input [ppmv]} - \text{pollutant at exposure [ppmv]}}{\text{pollutant input [ppmv]}} \times 100$$

This calculation simply comes down to dividing the removed by the initial pollution (in ppmv). Attention should be paid to the fact that this approach does not take into account the quantity of the photocatalytic material used to bring about this conversion, nor the exact intake of the pollutant (Verbruggen, 2009).

Secondly, one could express the obtained conversion in ppmv/g which can be calculated by means of the following formula (Verbruggen, 2009).

$$\text{Conversion } \left[\frac{\text{ppmv}}{\text{g}}\right] = \frac{\text{pollutant input [ppmv]} - \text{pollutant at exposure [ppmv]}}{\text{mass input of active photocatalyst [g]}}$$

Once again, this formula can be interpreted very easily. In this case the removed pollution (in ppmv) is divided by the mass of the active photocatalyst used (in gram). So, the formula expresses how many ppmv of acetaldehyde can be removed on average by a single gram of a photocatalyst and thus indicates the differences in reactivity existing between several types of photocatalysts. Active materials will experience a high conversion even when a limited amount of photocatalyst was used. This particular catalytic quantity is very useful in the context of this thesis because a slightly different input of mass was used for each photocatalyst. These variations arise from the coating process (which is used to form a deposition of photocatalytic material on glass beads that are to be exposed to UV light) and cannot be prevented entirely. Attempts have been made however, to keep the variations as small as possible. Some further remarks are needed here. First of all, only the active quantity of a photocatalyst is being considered. Furthermore, it is assumed that all photocatalytic material is 100% active; an assumption which does not always apply (Verbruggen, 2009). As more photocatalytic material is added, its marginal efficiency decreases. This implies that the conversion in ppmv/g represents the average amount of acetaldehyde (in ppmv) that can be removed by a single gram of a photocatalyst given a certain total input of mass of this photocatalytic material.

This dependency of the conversion (in ppmv/g) on the total input of mass of a photocatalyst can be proven. This is done for the commercially available photocatalyst AEROXIDE ® TiO_2 P25. Figure 5 shows, by means of a trendline based on empirical findings (susceptible of small errors), for acetaldehyde intake levels fluctuating both around 110 ppmv and around 175 ppmv, that the more of this material is used (in gram), the larger the converted share of the acetaldehyde input (in %). However, the marginal contribution to the conversion of acetaldehyde of each single gram of the material declines as the total mass of this material increases. The latter phenomenon is comparable to the law of diminishing marginal returns in economics. Note that conversion is expressed in percentage to take the slightly fluctuating acetaldehyde intake level into account. If this level had been constant for all different mass inputs, conversion could have been expressed in ppmv.

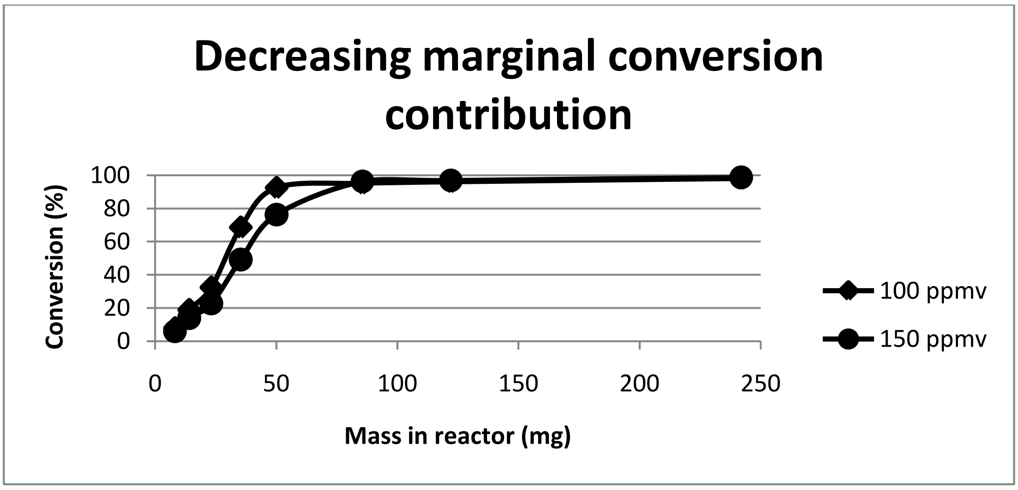

Figure 5. Decreasing marginal conversion contribution of P25

As more photocatalytic material is used, the increase in acetaldehyde conversion becomes smaller. Nevertheless, the increase in costs remains constant (linear relationship). Therefore, adding photocatalytic material is advisable as long as it leads to a higher increase in conversion compared to the increase in costs (both in terms of percentage). At a certain mass input, the increase in conversion and costs will be equal to one another. Adding more photocatalytic mass would lead to a higher increase in costs compared to the increase in conversion and thus would not be economically worthwhile. This can be represented graphically by examining the course of the conversion (in %) per euro at an acetaldehyde intake level of 110 ppmv and 175 ppmv which is represented in Figure 6 by means of a trendline based on empirical findings (susceptible of small errors). Adding extra photocatalytic material is advisable as long as the conversion (in %) per euro rises. The optimal mass input is the situation at which the conversion (in %) per euro is at its maximum. Obviously, this maximum depends on the acetaldehyde intake level (the lower the intake level, the smaller the amount of photocatalytic material needed).

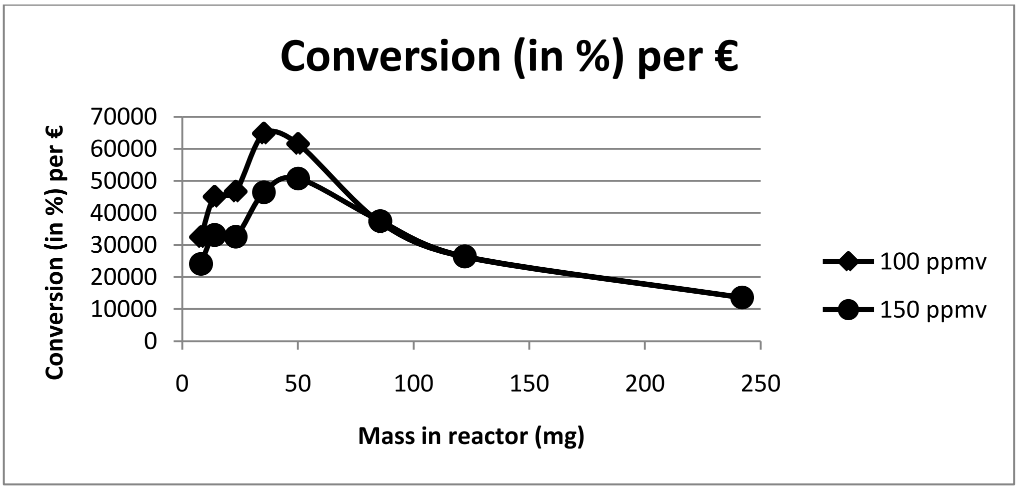

Figure 6. Conversion (in %) per euro of P25

To recapitulate, attention has to be paid when comparing the conversion in ppmv/g of different photocatalysts (which is the case in the computation of the ICER) due to the dependence of this catalytic quantity on the total mass used of a photocatalysts. This measure can only be compared correctly when the exact same amount of mass was used for each photocatalyst. As stated earlier, this is not entirely the case as slight variations in the mass input of the different photocatalysts that are to be compared arise from the coating process (Verbruggen, 2009).

Despite the reasoning mentioned above, it was preferred to compare the alternatives based on their conversion in ppmv/g to take the insuperable differences in mass input between the photocatalysts into account. Meanwhile, it is acknowledged that the chosen catalytic quantity ignores the decreasing marginal efficiency of a gram of photocatalytic material. It is believed, however, that the variations in mass input of the materials that are to be compared are relatively small thanks to the cautious execution of the coating process and that the utilization of the catalytic quantity only leads to a limited, negligible error. In other words, applying this catalytic quantity can be justified when the variation in mass input is small. On the other hand, when these differences become rather large, these materials cannot be compared directly.

3.2.1.1.2.2 Costs

With regard to the costs; these will be expressed in euros. The prices per kilo, of all commercially available photocatalysts that were tested, were obtained. These were then converted into prices per gram which can be compared directly to the conversions in ppmv/g. To calculate the total price paid for each photocatalyst in its own experimental design (i.e. taking the used mass of each photocatalyst in account), the price per gram simply was multiplied by the mass used. The latter value can be compared with the conversion percentage.

3.2.1.1.3 Commercial photocatalysts

The effectiveness in reducing the acetaldehyde level inside a reactor was tested for several commercially available photocatalysts (Table 1). The obtained conversion in percent and ppmv/g was measured at two different acetaldehyde intake levels, being 110 ppmv and 175 ppmv. For P25, 50.1 mg of material was used to test its conversion capability at both intake levels. Figure 5 and 6 clearly show that, at this specific mass input, the conversions measured at both intake levels differ considerably. This stresses the relevancy of measuring at different intake levels. Next, a CEA is performed to look for the most cost-effective alternative. Both the ACER and the ICER were computed. Because the results of the CEA at an acetaldehyde intake level of 175 ppmv resemble the ones found in case of an intake level of 110 ppmv, they were to form part of the appendices.

Table 1. Commercial photocatalysts

MATERIAL		**SUPPLIER**	**PRICE***
Name	Specifications		€/g
P25	AEROXIDE® TiO_2 P25	Acros Organics	0.0300 *(instead of 0.1062)*
TiO_2 Aerolyst	P25 Aerolyst® 7710	Evonik	1.6000
Hombikat	Hombikat, TiO_2, ≥ 95,0%, catalyst grade	Sigma-Aldrich	0.2476
Millenium	Millenium PC500	Chrystal Globe	0.0250
P90	AEROXIDE® TiO_2 P90	Evonik	0.0330
PF2	AEROXIDE® TiO_2 PF2	Evonik	0.0900

* Each price has been obtained by means of personal communication with the supplier.

It should be noted that in all calculations the price of P25 when bought from Evonik's distributor Necarbo was used instead of the price of Acros Organics which was the actual supplier because of the profound effect of this specific price on the ICER. This was only possible because the product is identical irrespective of the supplier.

3.2.1.1.3.1 ACER

For each commercially available photocatalyst the ACER was calculated at an acetaldehyde intake level of 110 ppmv. As mentioned earlier, the lower this value, the better. Tables 2 summarizes the findings.

Table 2. ACERs of commercial photocatalysts at 110 ppmv acetaldehyde intake

MATERIAL	MASS IN REACTOR	PRICE	CONVERSION	ACER Conversion (%)	CONVERSION	ACER Conversion (ppmv/g)
	g	€/g	%	10^{-6}€/%	ppmv/g	10^{-6}€/ppm
P25	0.0501	0.0300	92.50	16.25	2043.87	14.68
TiO2 Aerolyst	0.0487	1.6000	73.35	1062.37	1558.36	1026.72
Hombikat	0.0589	0.2476	94.45	154.40	1714.88	144.38
Millenium	0.0500	0.0250	100.10	12.49	2169.37	11.52
P90	0.0654	0.0330	97.44	22.15	1649.79	20.00
PF2	0.0609	0.0900	2.34	2347.27	42.63	2111.39

Irrespective of the catalytic quantity used, Millenium (which has the lowest cost and the highest conversion) has the lowest ACER and is followed by P25, P90 (which both have a reasonably low cost and rather high conversion), Hombikat, TiO_2 Aerolyst and PF2 respectively. Based on these findings Millenium is the preferred photocatalyst. Remarkably, both TiO_2 Aerolyst and PF2, which are not recommended for photocatalysis by their producers, have a high ACER. This subject will be returned to later on.

This can also be depicted graphically as the following histograms (Figure 7 and 8) prove.

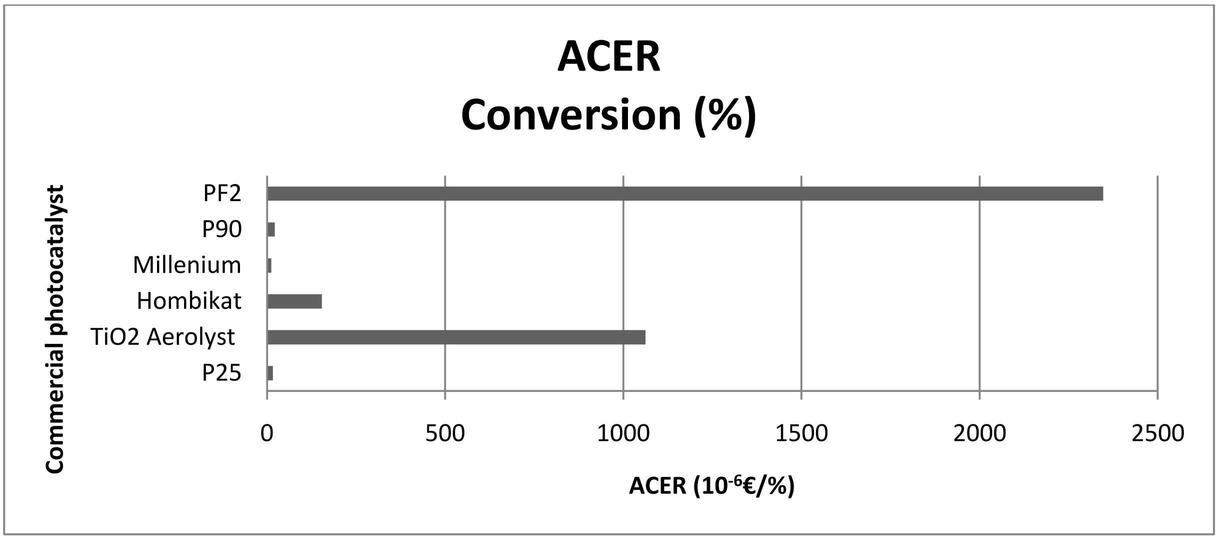

Figure 7. ACERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in percentage

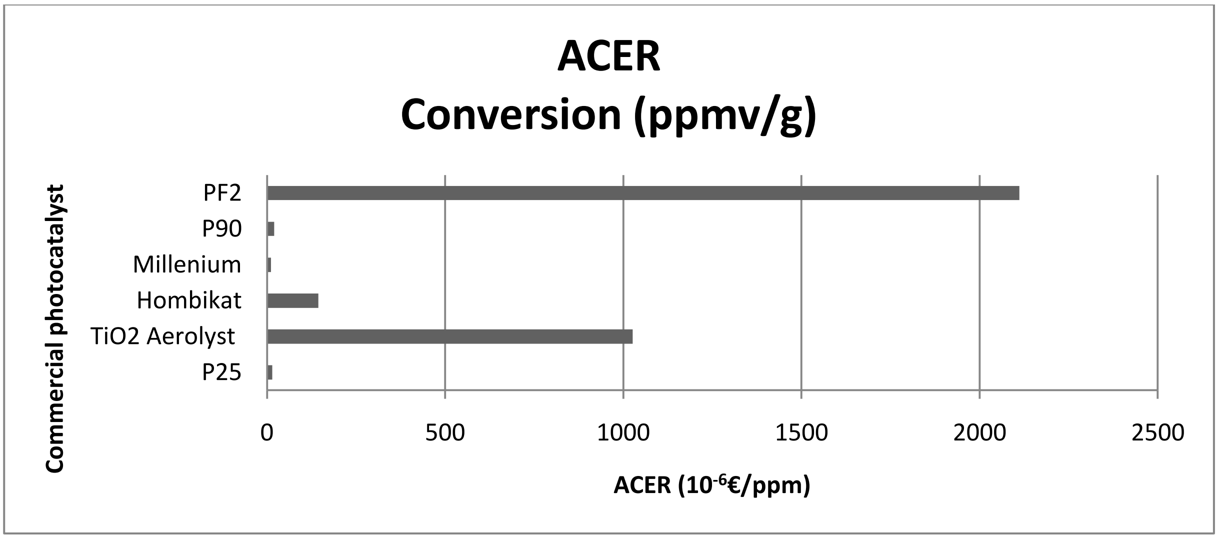

Figure 8. ACERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in ppmv/g

Obviously, these figures lead to the exact same conclusion. One could suggest however, that the results of the ACER calculations are somewhat more amenable when they are presented graphically.

The conclusion presented above is not very sensitive to changes in price. Some simple mathematical calculations prove that Millenium's price will have to rise with more than 30.12 % (to 32.53 €/mg) for conversion in percentage and with more than 27.38 % (to 31.84 €/mg) for conversion in ppmv/g to alter the conclusion. In both cases these rather large price changes will be in favor of P25.

The findings in case of an acetaldehyde intake level of 175 ppmv can be found in Appendix I.

3.2.1.1.3.2 ICER

To be able to calculate the ICER, a reference standard has to be chosen first to compare each (tested) commercially available photocatalyst to. The reference standard chosen in this thesis is P25. As literature points out, P25 is one of the most efficient commercially available photocatalysts (Piscopo, Robert, & Weber, 2001). Evonik, a producer of this material, even claims on its website that its AEROXIDE® TiO_2 P25 is recognized as the 'gold standard' in photocatalysis (Evonik, n.d.).

The ICERs were computed based on the conversions expressed in percentage measured at an acetaldehyde intake level of 110 ppmv and are depicted by means of a CE plane (Figure 9). The graphical approach is preferred in this case because the ICER on its own has no unambiguous explanation. A negative value, for example, could represent both an alternative in quadrant IV which is very promising and an alternative in quadrant II which cannot be recommended. So in this case a picture really is worth a thousand words!

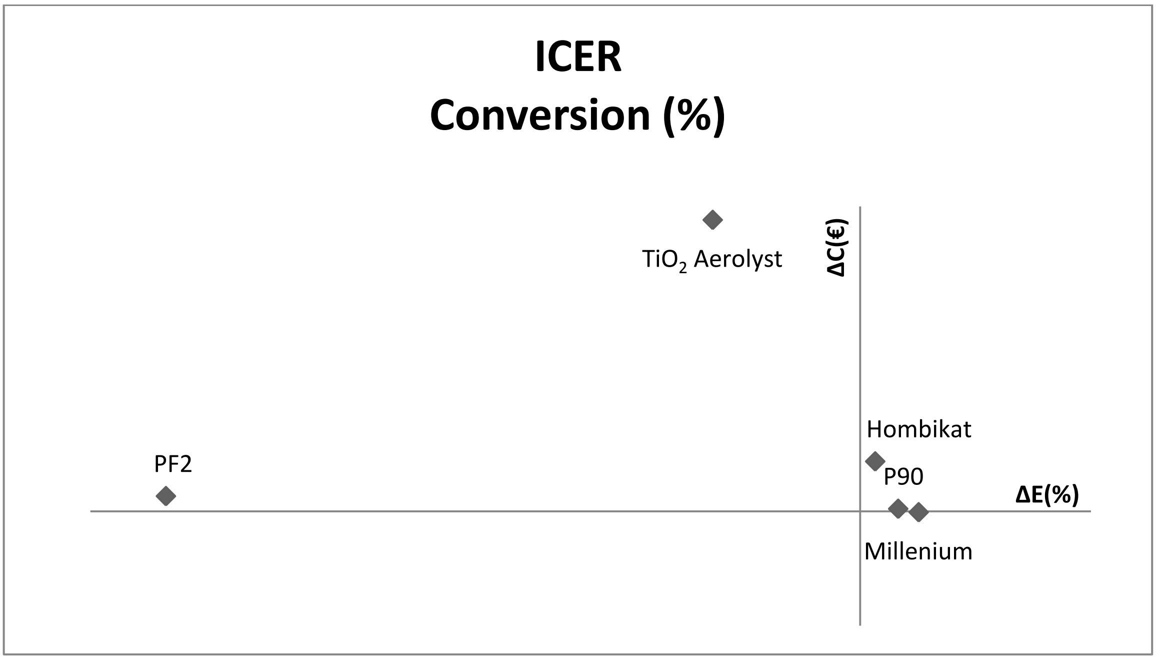

Figure 9. ICERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in percentage

Figure 9 proves that both TiO_2 Aerolyst and PF2 need not receive further consideration. Compared to P25, these alternatives cost more (in €) and convert less (in %). In the case of Hombikat and P90 however, the evaluation is slightly more difficult. Clearly, a trade-off can be made between the conversion (in %) of these materials and the associated cost (in €). To be able to determine whether the cost-effectiveness is sufficient, a value K has to be chosen. K represents the amount (in €) one is willing to pay to raise the conversion by 1 %. Given the fact that Millenium brings about the best conversion at the lowest cost (compared to all other commercial photocatalysts) (graphically the lowest and most right hand position), Millenium will be the best option independent of the value one sets for K. Note that the conclusions drawn based on the ACERs and ICERs of the commercial photocatalysts are comparable.

Since the prices of the different photocatalytic materials can be expected to change over time, it is important to look at the sensitivity of the results to such price fluctuations. This section discusses several possible scenarios.

Scenario A: Millenium's price can increase up to 20.24 % (from 25.00 to 30.06 €/mg) without altering the conclusions drawn above. At a price of 30.06 €/mg, the Millenium sample would cost as much as the sample of the reference standard P25 (that is €0.0015), but it would still bring about a higher conversion. Graphically this can be depicted by an upward shift from Millenium's original position into a new position on the horizontal axis to the right of the origin (Figure 10).

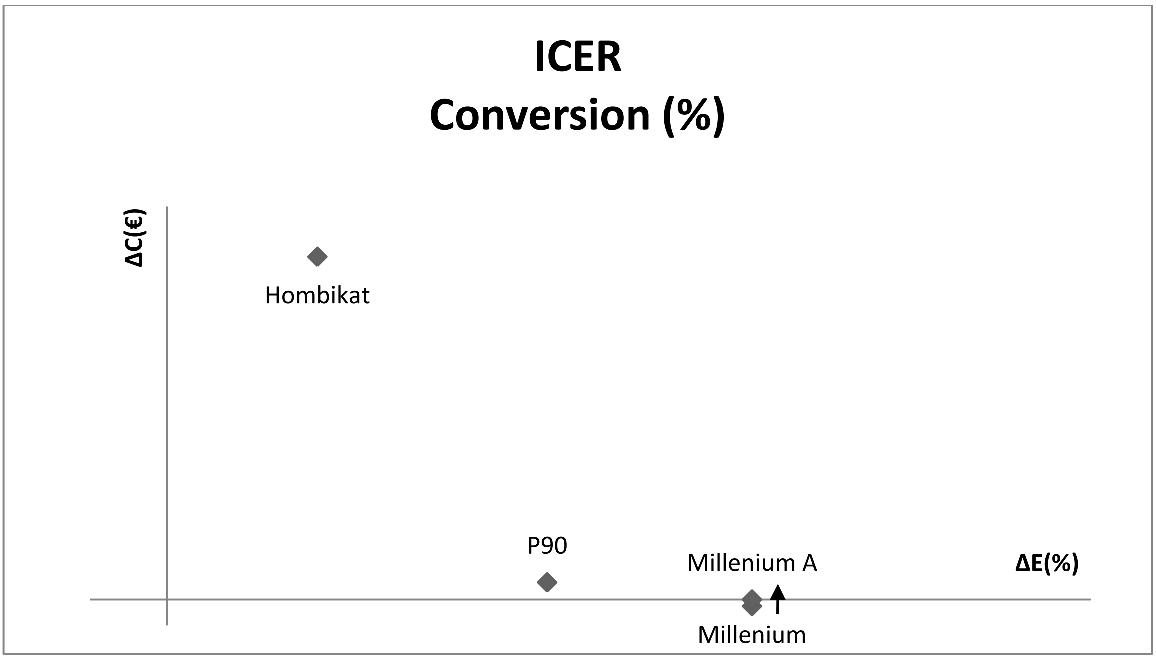

Figure 10. Sensitivity of ICERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario A

Scenario B: Now suppose Millenium's price increases more than 20.24 % (to more than 30.06 €/mg) and K falls between 0 and 1.33×10^{-4}. The cost of the Millenium sample would amount to more than €0.0015. The maximum value for K is the slope of the straight line crossing both the origin and P90 and thus equals the ICER of P90. When K is equal to this maximum value and Millenium is situated to the right of the straight line through the origin, this photocatalyst is always more appealing than P25, P90 (which are advisable to the same extent) and Hombikat. When K is smaller than the maximum value (but positive) and Millenium is still positioned to the right of the straight line, this photocatalysts again outperforms P25. In this case, both P90 and Hombikat are situated to the left of the straight line which makes them unattractive alternatives. If Millenium would be positioned to the left of the straight line, the latter conclusion also holds for this material. When Millenium's price amounts exactly to 50.22 €/mg (with the sample now costing €0.0025) and K amounts to 1.33×10^{-4}, P25, P90 and Millenium would be equally interesting. Hombikat would not be advised. Graphically this scenario can be depicted by an upward shift from Millenium's position on the horizontal axis (scenario A) into a new position on the straight line through the origin and P90 (Figure 11).

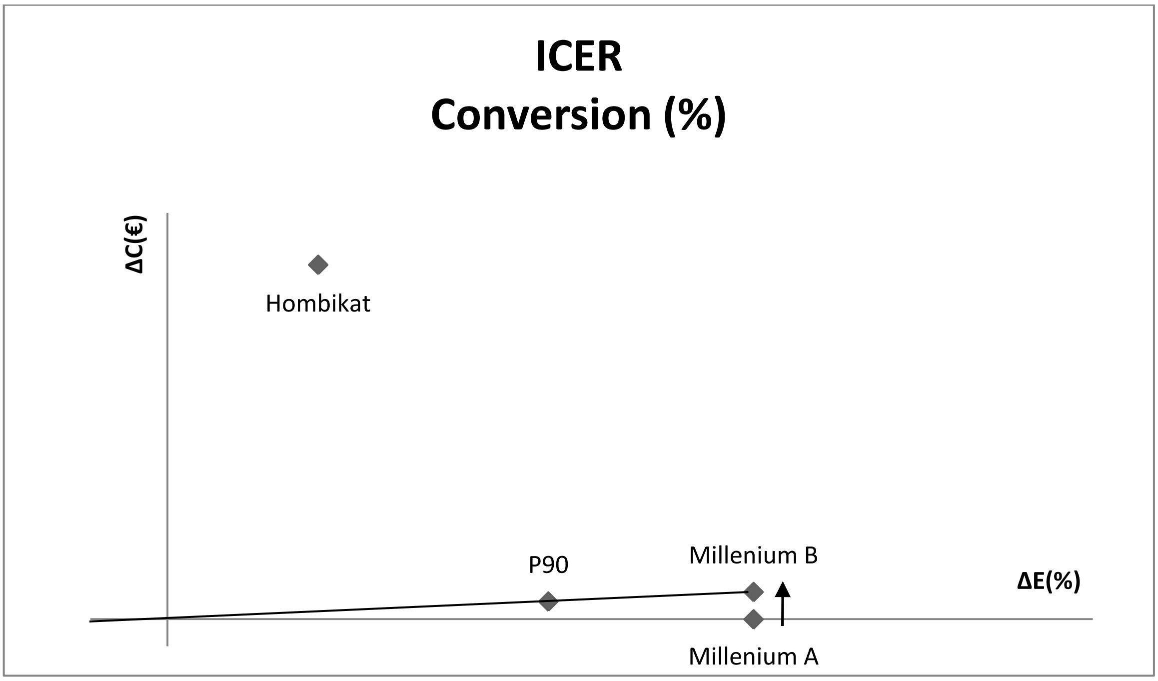

Figure 11. Sensitivity of ICERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario B

Scenario C: Suppose Millenium's price increases more than 100.90 % (to more than 50.22 €/mg) and K falls between 1.33x10^{-4} and 6.69x10^{-3}. The cost of the Millenium sample would amount to more than €0.0025. The maximum value for K is the slope of the straight line crossing both the origin and Hombikat and thus equals the ICER of Hombikat. An example is used to discuss this scenario in further detail. Figure 12 depicts a straight line through the origin with a slope K chosen from its range (dashed line). In its initial position, Millenium clearly is the best alternative situated the farthest to the right of this dashed line. P90 is the next best alternative, followed by the reference standard P25 and Hombikat (which performs worse than the reference). As Millenium's price starts to rise above 50.22 €/mg, the cost of the sample increases and Millenium moves upward. At a certain point, it will be situated exactly at the same distance from the dashed line as P90. In graphical terms this means that Millenium is positioned on the dotted line (which is parallel to the dashed line and intersect P90). In this case, Millenium and P90 are equally attractive in comparison with P25 while Hombikat can still be left unconsidered. Now imagine Milleniums price would go up some more, increasing the sample's cost even further. P90 now becomes the best alternative irrespective of Millenium's position. Firstly, if Millenium is situated between the dashed and the dotted line, it is the best alternative next to P90, followed by P25 and Hombikat (which still performs worse than the reference). Secondly, if Millenium lies on the dashed line, Millenium and P25 are equally appealing next to P90. Once again, Hombikat still underperforms the reference standard and can be forgotten. Finally, if Millenium is situated between the straight line with slope 6.69×10^{-3} and the dashed line, this sample (like Hombikat) is not to be considered any further because it is outperformed by the reference standard P25. P90 remains the advisable option as it is the only sample outperforming P25. The previous conclusion also holds when Millenium is situated on or above the straight line with slope 6.69×10^{-3}. Irrespective of the exact slope of the dashed line (the value chosen for K from the permitted range), a similar approach can be applied to discuss the rank of a certain alternative with regard to the other options.

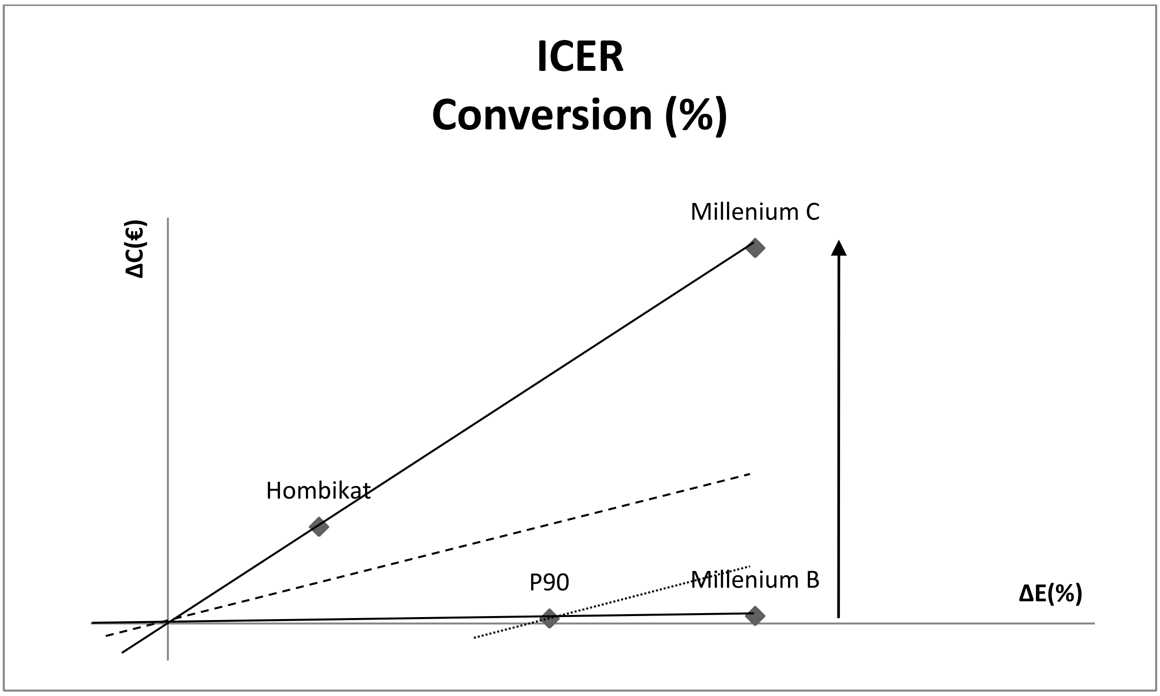

Figure 12. Sensitivity of ICERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario C(1)

The previous discussion is simplified when K amounts to 6.69×10^{-3}. As presented graphically in Figure 13, the dashed line coincides with the straight line having slope K. In this case, Hombikat is always equally appealing as the reference. As long as the cost of the Millenium sample remains reasonably low (below €0.0200 with Millenium's price amounting to 399.27 €/mg) and Millenium is situated below the dotted line which intersects P90 and is parallel to the straight line with slope $6.69x10^{-3}$ (or the dashed line), Millenium is the best alternative, followed by P90 and by both Hombikat and P25. When Millenium and P90 are both situated on the parallel, they are equally advisable in comparison with both Hombikat and P25. In this case, Millenium's price amounts to 399.27 €/mg and the sample costs €0.0200. When Millenium is situated above this dotted line but below the straight line with slope $6.69x10^{-3}$, P90 is the best option followed by Millenium and both Hombikat and P25. When Millenium is part of the straight line with slope $6.69x10^{-3}$, P90 is the only option outperforming the reference standard P25 (and both Millenium and Hombikat having a comparable performance). In this case, Millenium's price amounts to 1,047.04 €/mg and the sample costs €0.0524. When Millenium is situated above the straight line with slope $6.69x10^{-3}$, it is outperformed by P25 (and of course Hombikat), while P90 remains advisable.

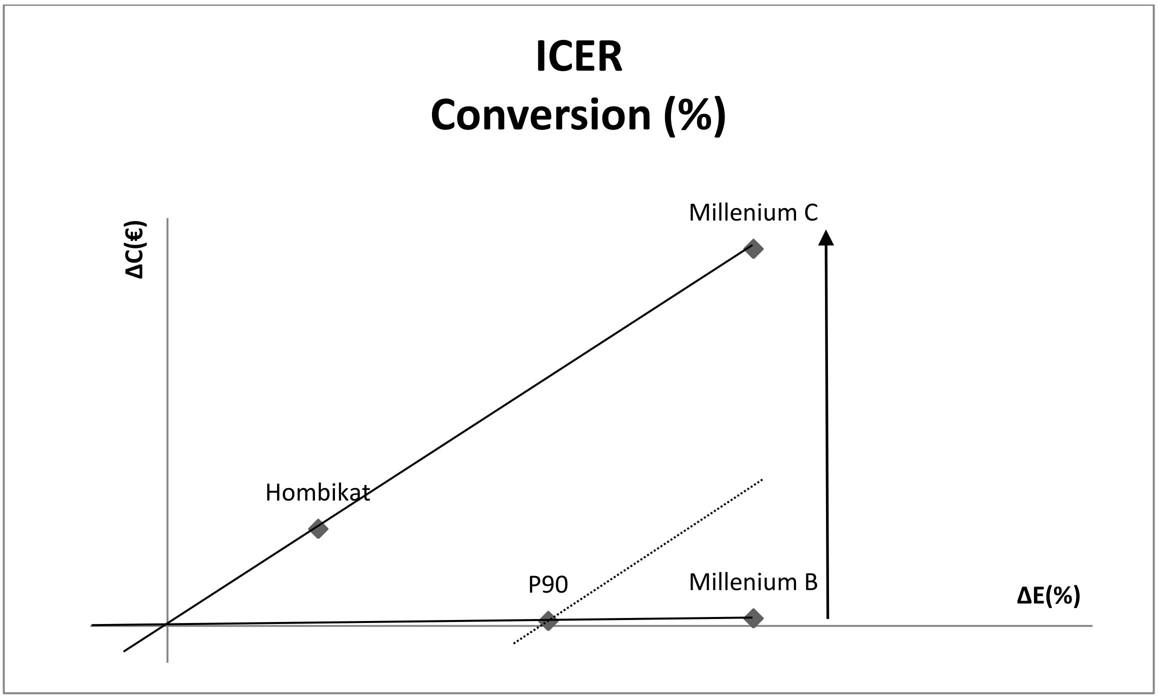

Figure 13. Sensitivity of ICERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario C(2)

Suppose Millenium's price increases more than 4,088.17 % (to more than 1,047.04 €/mg) and K amounts to more than $6.69x10^{-3}$. The cost of the Millenium sample would amount to more than €0.0524. Initially, in Figure 14, all three alternatives outperform the reference standard P25, with

Millenium being the best option, followed by P90 and Hombikat. As Millenium's price starts raising, the cost of that sample also increases. At a certain instant, P90 and Millenium will be equally appealing. In this case, Millenium is situated on the dotted line through P90 and parallel to the straight line through the origin with slope K. As Millenium's price goes up even further, P90 becomes the best alternative, followed by Millenium, Hombikat and P25. When Millenium and Hombikat are both situated on the dashed line having slope K and crossing through Hombikat, P90 is still the best option, but this time it is followed by both Millenium and Hombikat and the reference standard. If Millenium's price rises further without passing the straight line through the origin with slope K, it remains an acceptable option, but it is outperformed by both P90 and Hombikat. When Millenium is situated on the straight line though the origin with slope K, it is equally appealing as the reference standard. All other alternatives, being P90 and Hombikat, perform better. If Millenium's price goes up even further it turns into an inadvisable alternative that is outperformed by the reference standard. On the contrary, both P90 and Hombikat show better results than the reference.

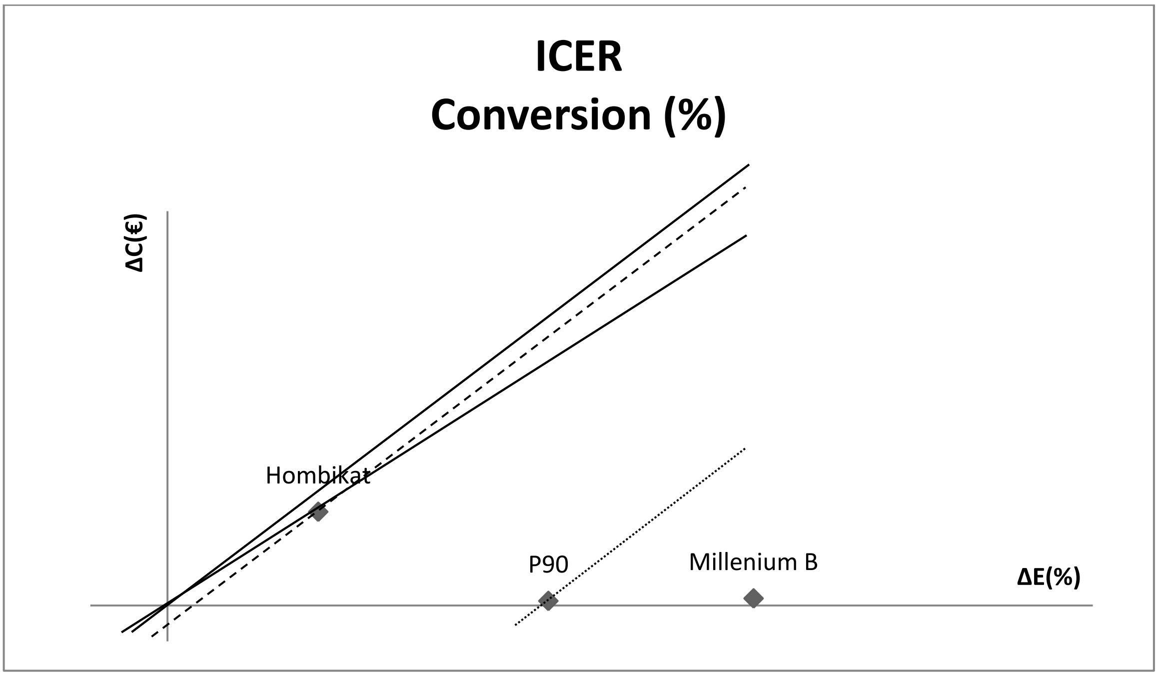

Figure 14. Sensitivity of ICERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario C(3)

Scenario B and C can only take place when Millenium's price increases by more than 20.24 % while all other prices remain unchanged. Because this is not a very realistic situation to expect, even in a not very competitive market, scenario A can be assumed to hold and no K value has to be determined.

The ICERs were also computed based on the conversions expressed in ppmv/g (Figure 15).

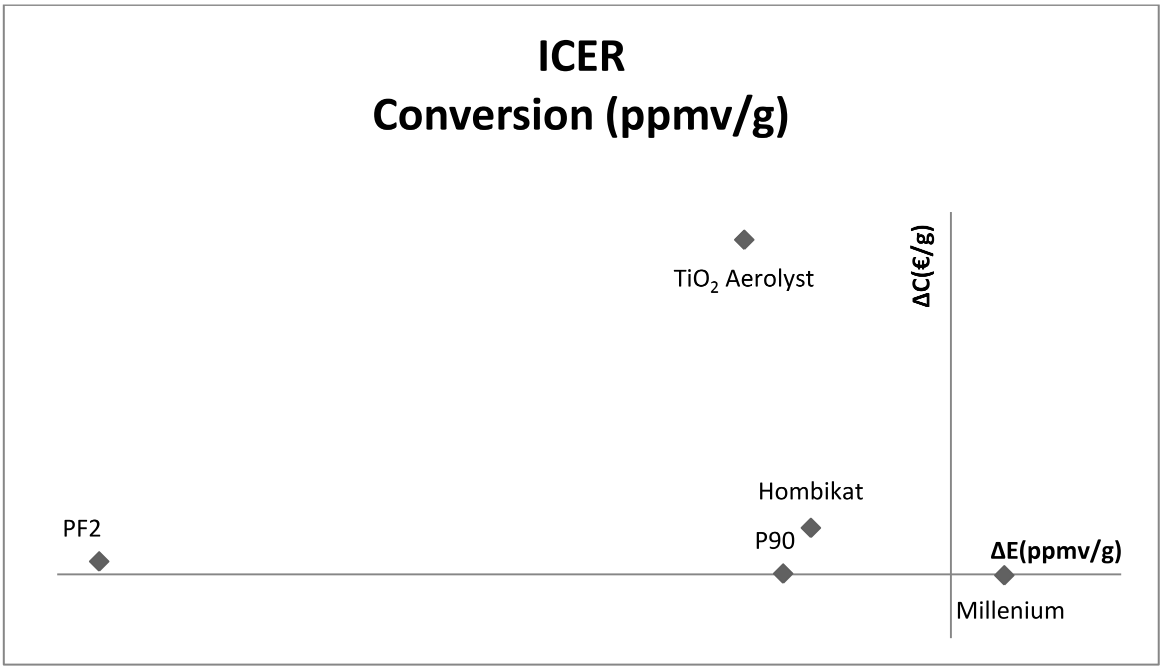

Figure 15. ICERs of commercial photocatalysts at 110 ppmv acetaldehyde intake with conversion in ppmv/g

When the insuperable differences in mass input between the commercial photocatalysts are taken into account, the CE plane changes slightly. Figure 15 is more clear-cut than its counterpart which expresses conversion in percentage (Figure 9). All alternatives, except Millenium, can be found in quadrant II. So, although each gram of a certain alternative costs more (in €/g) than a gram of P25, it converts less (in ppmv/g). Once again, Millenium will be chosen.

As was mentioned before, over time, the prices of the photocatalysts can be expected to vary which affects the results presented in Figure 15. Mainly Millenium should be kept an eye on, because an isolated price increase (leaving all other prices unchanged) could alter the results by shifting the product upwards into quadrant I. In this scenario, one will have to set a value K to determine whether Millenium would still outperform the reference standard being P25. However, Millenium’s price would have to rise with more than 20.00 % (from 25.00 to more than 30.00 €/mg) to bring about such a movement. Because it is rather unlikely to expect a single price to rise this much at once, it is opted not to switch over to a CBA by determining K.

To conclude, some further remarks are necessary here. Firstly, although Millenium clearly is the best option based on both the ACER and the ICER, this conclusion could change due to alterations in its price. However, only a rather large price increase is capable of this (as was proven above). Such a large increase will have to be based upon commercial objectives. Suppose instead that the increase is the result of a price growth of a raw material of Millenium (like TiO_2, the main raw material). If TiO_2 suddenly costs more, the other alternatives will be affected by this in a more or less equal manner because of the resemblances between all commercial photocatalysts tested. This will be reflected in a price increase for the alternatives with a certain percentage (which is roughly the same for Millenium and all its alternatives). This price increase will raise both the ACER and the ICER with this percentage only stressing the differences that already existed even further. Furthermore, based on this reasoning, one can expect that a sensitivity analysis by means of a Monte Carlo simulation will not lead to new conclusions. Therefore, it was deliberately decided upon not to perform such an analysis. The previous proves that price increases for a limited number of commercial photocatalysts can only be expected to result from commercial considerations. However, the question that remains is: “Which company would raise its price enough to affect the results of the CEA?”. Based on simple economic logic it can be concluded that no company would because this, most likely, will severely undermine that company’s competitive position.

Secondly, through means of the ICER’s, one can point out why TiO_2 Aerolyst and PF2 have a poor ACER. As mentioned earlier, neither one of both alternatives was made for photocatalytic applications. Nevertheless, TiO_2 Aerolysts effectiveness is surprisingly similar to the ones found for Hombikat and P90. In this case, it was the high price of this material that caused the high ACER. The unexpected positive findings for TiO_2 Aerolyst stimulated the research team to also test PF2. Unfortunately, although the price of this photocatalyst is much lower than the price of TiO_2 Aerolyst, its effectiveness was extremely poor which lead to the high ACER. So, to conclude, neither TiO_2 Aerolyst nor PF2 is recommendable in this specific context, but both for different reasons.

The findings in case of an acetaldehyde intake level of 175 ppmv can be found in Appendix II.

3.2.1.1.4 Synthetic photocatalysts

The effectiveness in reducing the acetaldehyde level inside a reactor was also tested for several photocatalytic materials prepared manually in an academic research centre. Table 3 shows an overall picture of the different samples made, each described by means of an abbreviated name. The table also indicates which preparation method (described in scientific articles) was used and possible modifications that were made to this method in an attempt to improve its photocatalytic activity. Again, the obtained conversion in percent and ppmv/g was measured at two different acetaldehyde intake levels (being 110 ppmv and 175 ppmv). Once again, the results in case of an acetaldehyde intake level of 175 ppmv can be found in the appendices. A CEA is performed to search for the most cost-effective alternative. Both the ACER and the ICER were computed.

Table 3. Synthetic photocatalysts

MATERIAL		
Name	Specifications	Scientific source
NP1	Titanium dioxide nanoparticles preparation 1	Addamo et al., 2004
NP1 etched	Titanium dioxide nanoparticles preparation 1, etched glass beads (with KOH)	Addamo et al., 2004
NP1W5h	Titanium dioxide nanoparticles preparation 1, calcination 5h, addition of water (and ethanol) for suspending the powder after calcination	Addamo et al., 2004
NP3	Titanium dioxide nanoparticles preparation 3	Addamo et al., 2004
NPW3	Titanium dioxide nanoparticles preparation 3, dried powder in water/ethanol and calcination	Addamo et al., 2004
TiO_2/SnO_2 (190/10)	Titanium dioxide nanoparticles preparation 1 (190 mg) and tin dioxide nanoparticles (10 mg)	Addamo et al., 2004; Aprile, Teruel, Alvaro, & Garcia, 2009
TiO_2/SnO_2 (180/20)	Titanium dioxide nanoparticles preparation 1 (180 mg) and tin dioxide nanoparticles (20 mg)	Addamo et al., 2004; Aprile et al., 2009
TiO_2/SnO_2 (160/40)	Titanium dioxide nanoparticles preparation 1 (160 mg) and tin dioxide nanoparticles (40 mg)	Addamo et al., 2004; Aprile et al., 2009
TiO_2/SnO_2 (140/60)	Titanium dioxide nanoparticles preparation 1 (140 mg) and tin dioxide nanoparticles (60 mg)	Addamo et al., 2004; Aprile et al., 2009
Rachel1	Rachel material 1	Rachel et al., 2002
Rachel1W	Rachel material 1, suspension dried, calcination, addition of water for suspending	Rachel et al., 2002
Rachel3	Rachel material 3	Rachel et al., 2002
Rachel3W	Rachel material 3, suspension dried, calcination, addition of water for suspending	Rachel et al., 2002
Rachel3W500	Rachel material 3, suspension dried, calcination (500°C), addition of water for suspending	Rachel et al., 2002

Rachel3W500(2)	Rachel material 3, suspension dried, calcination (500°C), addition of water for suspending	Rachel et al., 2002
Sonowane	Sonowane	Sonawane, Hegde, & Dongare, 2003
Lim	Lim	Lim, Lynch, & In, 2009
Lim5h	Lim, calcination 5h	Lim et al., 2009
Rachel3 Ag0.5wt%	Rachel material 3, doped with silver (0.5 wt%), suspension dried, calcination (450°C), addition of water for suspending	Rachel et al., 2002
Rachel3 Ag1.0wt%	Rachel material 3, doped with silver (1.0 wt%), suspension dried, calcination (450°C), addition of water for suspending	Rachel et al., 2002
Rachel3 Ag1.5wt%	Rachel material 3, doped with silver (1.5 wt%), suspension dried, calcination (450°C), addition of water for suspending	Rachel et al., 2002
Rachel3 Bio-Ag0.5wt%	Rachel material 3, doped with bio-silver (0.5 wt%), suspension dried, calcination (450°C), addition of water for suspending	Rachel et al., 2002

An overview of the main cost units of each sample is given in Appendix III. A few extra notes are necessary here. Firstly, some of the material used to coat did not stick to the glass beads and thus was not used any further. Because this loss of material cannot be prevented entirely, all material used to coat was taken into account to determine the cost of the different samples, whether it eventually became part of the coating or not. However, to calculate the conversion of the samples in ppmv/g only the material that became part of the coating was taken into account, because this was the only material that was exposed to UV light.

Secondly, often when devices consuming energy were applied, several samples were treated at once. Some devices were used at their maximum capacity (e.g. three samples at once in the ultrasonification bath). In this case, the costs associated with energy consumption were spread over the different samples that were treated. Other devices, on the other hand, were not always applied optimally (e.g. the calcinations oven). One could decide that the few samples treated should carry all of the energy costs. This, however, would weigh heavily on the total cost of the samples while, in a more optimal situation, this would not have been necessary. Therefore, in case the device was not used to its full potential, an approximation of the number of samples that could have been treated if the device was used at a more or less acceptable capacity (less than the maximum capacity) was made and the cost were spread over this number of samples. This way, the tested samples carry a more realistic amount of the energy costs. Some devices (e.g. the drying oven), besides not being used to their full potential, were employed by other researchers at the same time. In these cases the previous reasoning was also followed.

3.2.1.1.4.1 ACER

The ACER of each of the synthetic photocatalyst presented above was calculated at an acetaldehyde intake level of 110 ppmv. As mentioned earlier, the material with the lowest ACER is the most appealing. Table 4 presents the findings. Recall that photocatalysts can only be compared without making a considerable error when the mass input of the materials is more or less the same. This is not always the case for the samples of synthetic photocatalytic material. Therefore, when discussing the ACERs, only samples with a more or less equivalent mass input are compared.

Table 4. ACERs of synthetic photocatalysts at 110 ppmv acetaldehyde intake and high kilowatt-hour cost

MATERIAL	**MASS IN REACTOR**	**PRICE**	**CONVER-SION**	**ACER Conversion (%)**	**CONVER-SION**	**ACER Conversion (ppmv/g)**
	g	€	%	€/%	ppmv/g	€/ppmv
NP1	0.1112	1.0024	6.80	0.1473	69.79	0.1292
NP1 etched	0.1746	1.1892	11.62	0.1023	71.04	0.0959
NP1W5h	0.0795	0.2519	33.66	0.0075	501.28	0.0063
NP3	0.0432	0.9184	34.72	0.0265	943.39	0.0225
NPW3	0.1228	0.9075	63.52	0.0143	631.11	0.0117
TiO2/SnO2 (190/10)	0.0979	1.0794	40.56	0.0266	502.27	0.0220
TiO2/SnO2 (180/20)	0.0931	1.1059	32.42	0.0341	421.62	0.0282
TiO2/SnO2 (160/40)	0.0910	1.1591	28.43	0.0408	372.45	0.0342
TiO2/SnO2 (140/60)	0.1001	1.2122	22.42	0.0541	267.00	0.0454
Rachel1	0.0600	0.3604	9.94	0.0363	192.24	0.0312
Rachel1W	0.0654	0.2061	38.12	0.0054	693.66	0.0045
Rachel3	0.0549	0.3566	1.20	0.2979	24.39	0.2663
Rachel3W	0.0507	0.2568	82.71	0.0031	1923.34	0.0026
Rachel3W500	0.0577	0.2596	67.40	0.0039	1362.62	0.0033
Rachel3W500(2)	0.0604	0.2593	64.89	0.0040	1277.61	0.0034
Sonowane	0.0514	0.2148	4.78	0.0449	103.45	0.0404
Lim	0.1322	0.3565	24.61	0.0145	214.05	0.0126
Lim5h	0.0658	0.4840	1.92	0.2517	33.37	0.2204
Rachel3 Ag0.5wt%	0.0628	0.3169	40.66	0.0078	962.47	0.0052
Rachel3 Ag1.0wt%	0.0500	0.2983	42.20	0.0071	798.73	0.0075
Rachel3 Ag1.5wt%	0.0672	0.3216	39.34	0.0082	692.77	0.0069
Rachel3 Bio-Ag0.5wt%	0.0426	0.5650	30.53	0.0185	839.26	0.0158

Irrespective of the catalytic quantity used, Rachel3W turns out to have the highest conversion. By combining this conversion with a rather low cost, the sample ends up with the lowest ACER, followed immediately by Rachel3W500 and Rachel3W500(2). The latter samples (which are both variations of Rachel3W) were made in exactly the same way but the tested samples had a different amount of coating. The fact that Rachel3W, Rachel3W500 and Rachel3W500(2) perform this well, stresses the relevance of adding water for suspending. When comparing these samples with the one they were based on, being Rachel3, one can notice that the latter converts less and costs more (€0.0980 on average). The lower cost of the samples to which water was added for suspending mainly results from the fact that, for these samples, a certain amount of powder was calcened at once before it was coated on the glass beads. Therefore, the costs of this cost unit can be spread over all samples resulting from the coating process. When preparing Rachel3, the beads are coated before being calcened. Because the amount of samples that can be calcened at once is smaller than the amount of powder, the division factors vary (this can be verified in Appendix III.1) which affects the weight of the cost units. The same reasoning applies for Rachel1 and its variation Rachel1W (which seems to perform very well).

Next, when comparing the composite semiconductors (TiO_2/SnO_2 (190/10), (180/20), (160/40) and (140/60)) with NP1 (on which they are based), one can see that the former perform better. The increase in costs (resulting from extra ‘ingredients’ and ‘actions’ which can be verified in Appendix III.1) is (more than) compensated by the rise in conversion. Nevertheless, one should note that the variation of NP1, being NP1W5h, outperforms all other samples made out of TiO_2 nanoparticles. Once again, adding water for suspending lowers the calcinations cost of the sample remarkably. This low cost combined with an increased conversion (more or less at the level of the composite semiconductors) leads to the appealing ACER.

One can also see that the materials doped with commercially available silver (Rachel3 Ag0.5wt%, Ag1.0wt% and Ag1.5wt%) have a rather good ACER. Nevertheless, they are outperformed by Rachel3W (to which it is comparable) because of their higher costs and lower conversions. Next, one can note that Rachel3 Ag0.5wt% outperforms its biological counterpart which converts less and costs more.

The ACERs for both catalytic quantities can also be depicted graphically as the following histograms (Figure 16 and 17) prove. These figures obviously lead to the exact same conclusions.

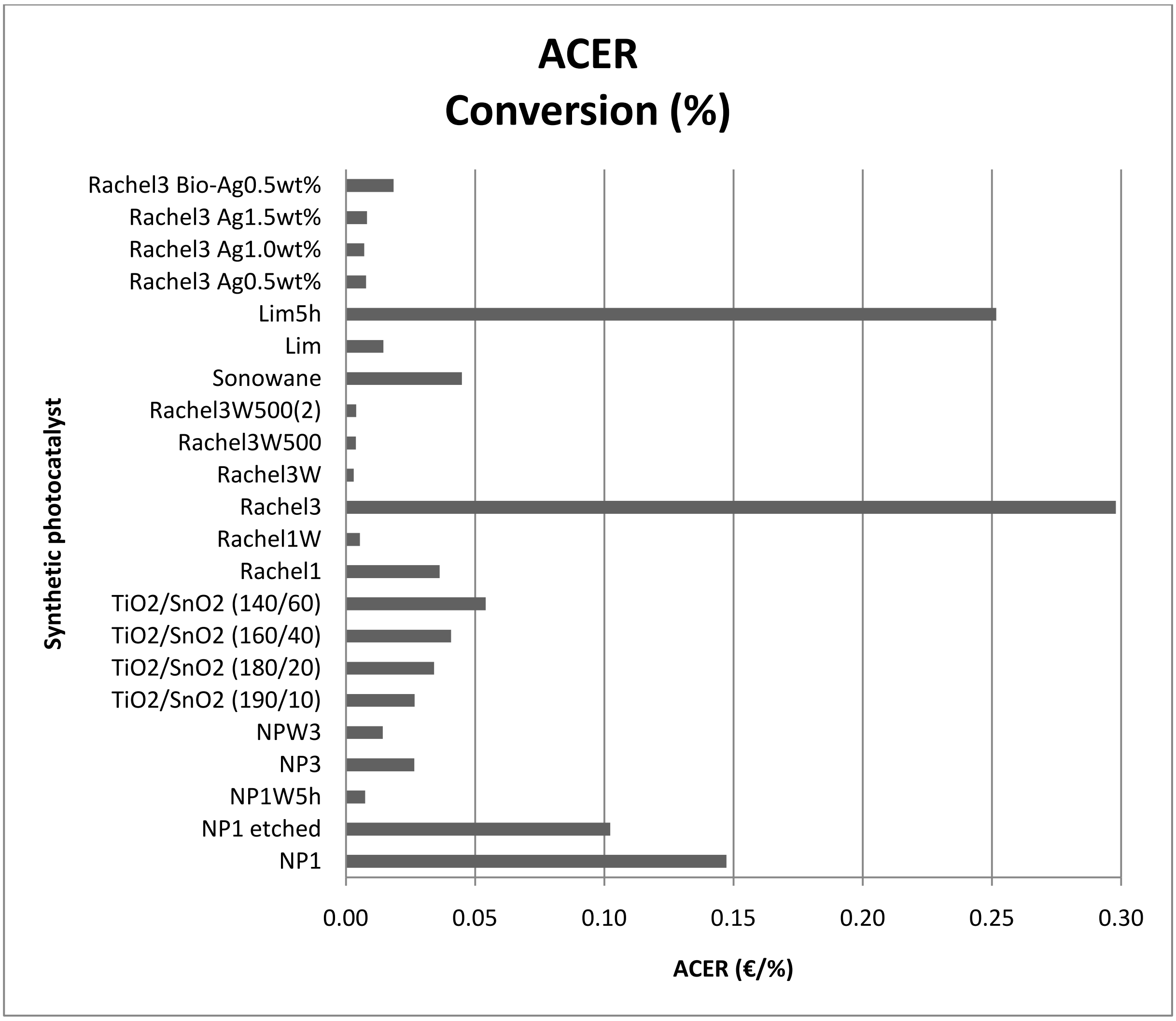

Figure 16. ACERs of synthetic photocatalysts at 110 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in percentage

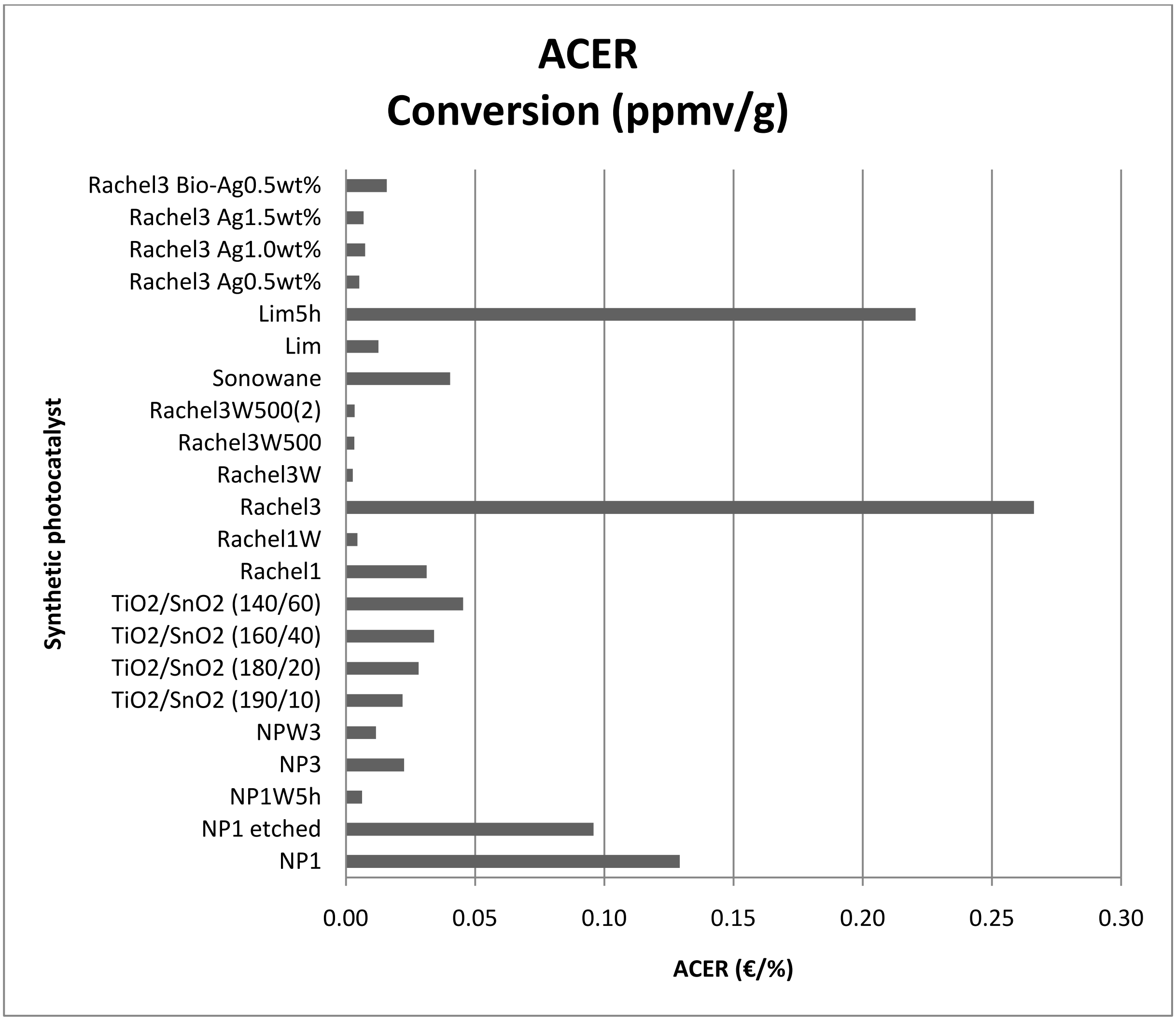

Figure 17. ACERs of synthetic photocatalysts at 110 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in ppmv/g

The conclusion drawn above is not very sensitive to price fluctuations. Rachel3W's cost will have to rise with more than 24.10 % (to €0.3186) for conversion in percentage and with more than 25.42 % (to €0.3220) for conversion in ppmv/g to alter the findings described above.

The findings in case of an acetaldehyde intake level of 175 ppmv can be found in Appendix IV.

3.2.1.1.4.2 ICER

As mentioned earlier, photocatalysts can only be compared without making a considerable error when the mass input of the materials is more or less the same. This is not always the case for the samples of synthetic photocatalytic material. Therefore, samples with a comparable mass input are grouped together while odd ones will be left out of the discussion. As Table 5 shows, two groups could be defined.

Table 5. Groups of synthetic photocatalysts to compute ICERs

MATERIAL	COATING
	mg
NP1	**111.2**
TiO2/SnO2 (190/10)	97.9
TiO2/SnO2 (180/20)	93.1
TiO2/SnO2 (160/40)	91.0
TiO2/SnO2 (140/60)	100.1
Rachel1	**60.0**
Rachel1W	65.4
Rachel3	54.9
Rachel3W	50.7
Rachel3W500	57.7
Rachel3W500(2)	60.4
Sonowane	51.4
Lim5h	65.8
Rachel3 Ag0.5wt%	62.8
Rachel3 Ag1.0wt%	50.0
Rachel3 Ag1.5wt%	67.2
Rachel3 Bio-Ag0.5wt%	42.6

In each group a reference standard was determined (printed in bold) to compare the remaining photocatalysts of that group with. The reference standard chosen in the first group is NP1. This is a rather obvious choice because all composite materials use TiO_2 nanoparticles (prepared like NP1) in combination with SnO_2 nanoparticles. Rachel1 is the reference standard in the second group because it is the easiest one to produce and is rather comparable to all other samples of that group.

For both groups, the ICER at an acetaldehyde intake level of 110 ppmv was computed. Figure 18 and 19 represent the results of the first group of samples.

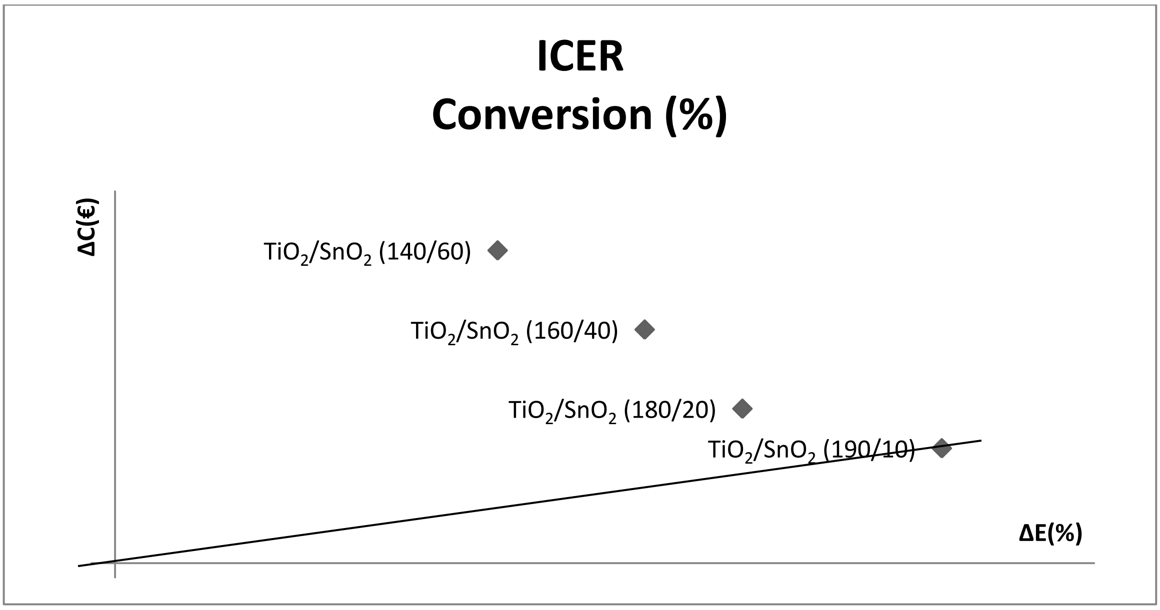

Figure 18. ICERs of synthetic photocatalysts of group 1 at 110 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in percentage

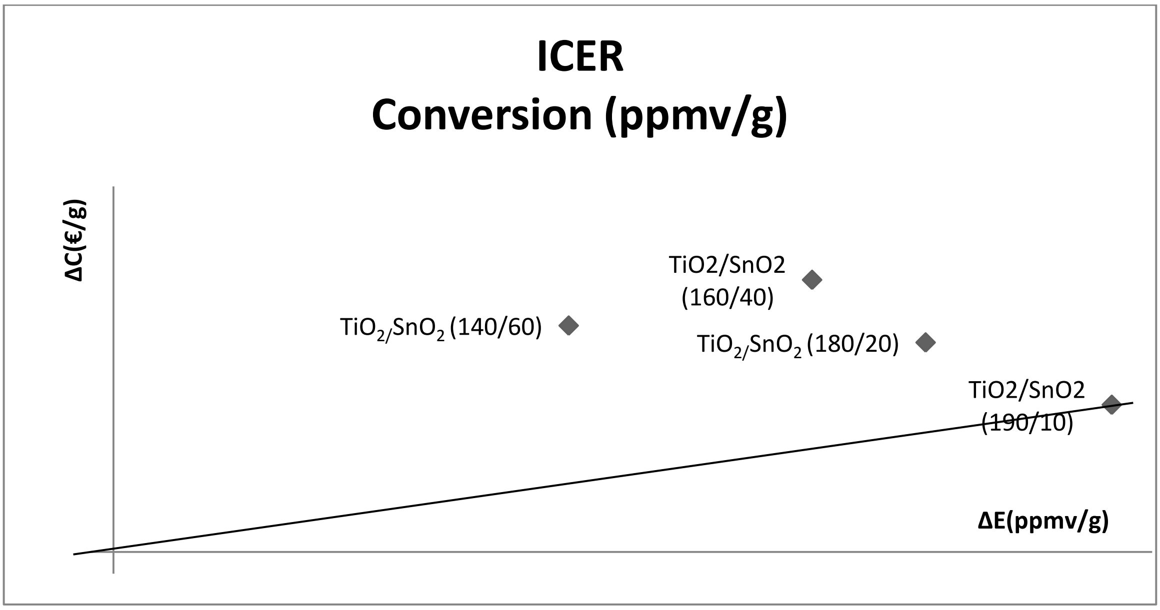

Figure 19. ICERs of synthetic photocatalysts of group 1 at 110 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in ppmv/g

Irrespective of the catalytic quantity used to express conversion, all composite materials are situated in quadrant I in which a value K has to be chosen to be able to determine whether these samples outperform the reference standard NP1 (note that based on the ACERs, the composite materials seemed to outperform NP1). Notice that TiO_2/SnO_2 (190/10) always is the lowest, most right hand sample. So, when K amounts to more than $2.28x10^{-3}$ (the slope of the straight line through the origin in Figure 18 that equals the ICER of the sample) in case conversion is expressed in percentage and $4.65x10^{-3}$ (the slope of the straight line through the origin in Figure 19 that equals the ICER of the sample) in the other case, this sample outperforms all others (the reference standard included). When K is smaller, the reference standard is optimal. When K is equal to these values, TiO_2/SnO_2 (190/10) and NP1 are equally appealing. Furthermore, when conversion is expressed in percentage, one can clearly observe that a higher share of SnO_2 leads to higher costs and lower conversions (the other catalytic quantity slightly sheds a different light on the matter). One can ask itself if it is economically worthwhile to make combinations of TiO_2 and SnO_2. Finally, be sure to note that the previous confirms the conclusions drawn based on the ACERs.

The next section discusses the results of the second group of samples. Figure 20 and 21 represent the ICERs of these samples at an acetaldehyde intake level of 110 ppmv.

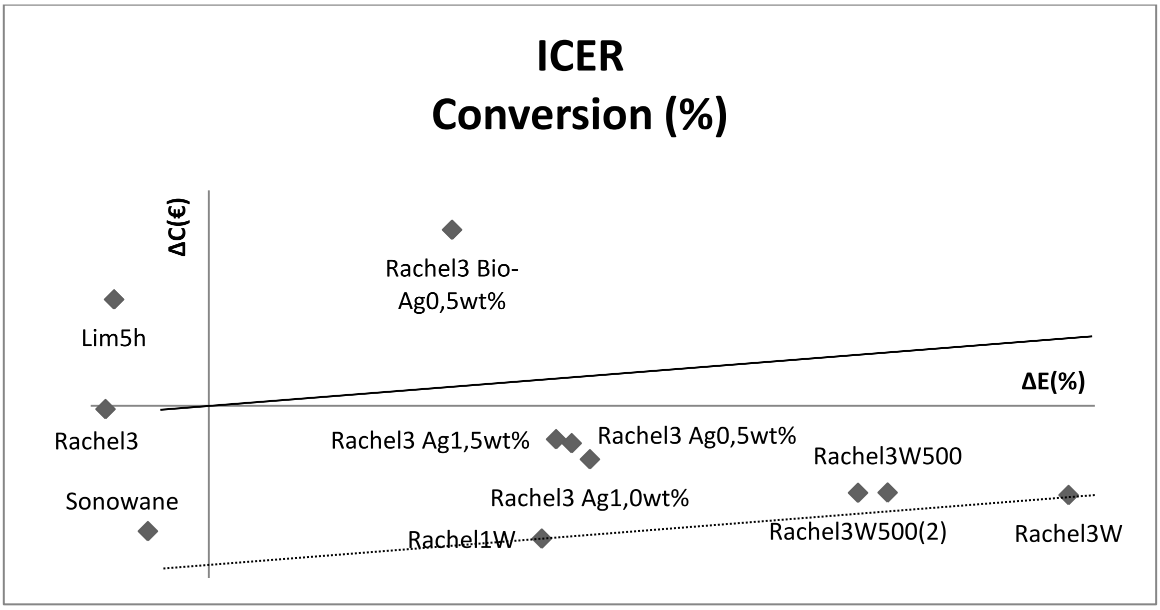

Figure 20. ICERs of synthetic photocatalysts of group 2 at 110 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in percentage

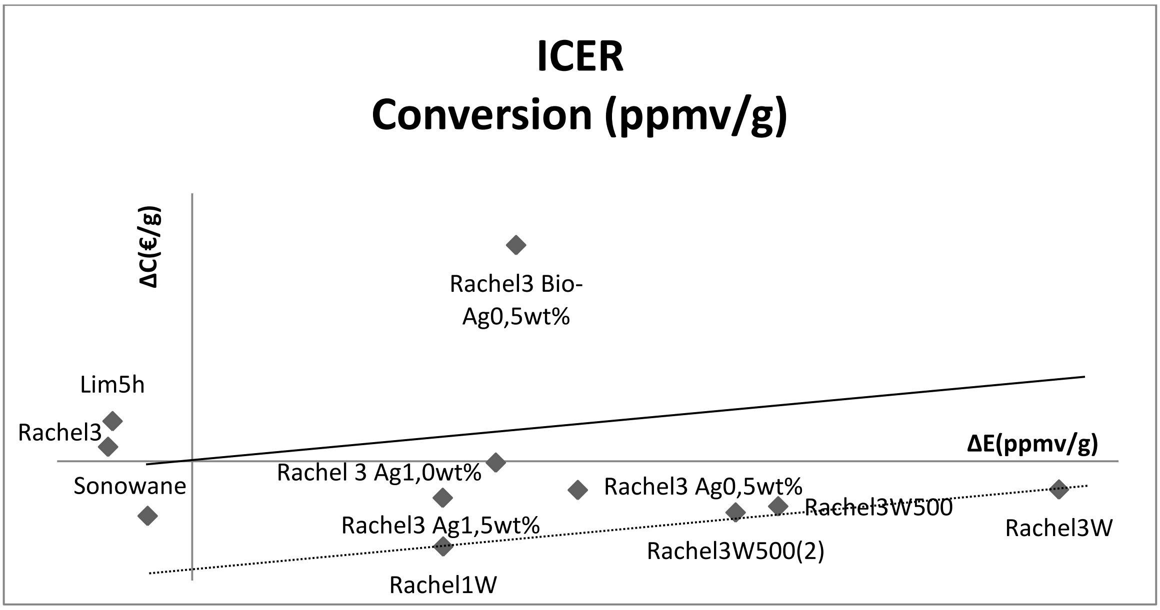

Figure 21. ICERs of synthetic photocatalysts of group 2 at 110 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in ppmv/g

Both figures show comparable result. The only difference is that, when conversion is expressed in ppmv/g, Rachel3 is situated in quadrant II, which makes it an unappealing option, whereas when conversion in percentage is used, the sample lies in quadrant III in which a value K has to be chosen to determine whether it outperforms the reference standard being Rachel1. If both figures are taken into account at the same time, it is decided not to deal with Rachel3 any further. Irrespective of the catalytic quantity chosen, Rachel3 Bio-Ag0,5wt% is situated in quadrant I and Sonowane in quadrant III. In both quadrants a value K has to be determined to be able to give judgement. Lim5h is always situated in the inadvisable quadrant II. All other samples, being Rachel1W, Rachel3W, Rachel3W500, Rachel3W500(2) and Rachel3 Ag0.5wt%, Ag1.0wt% and Ag1.5wt%, are situated in quadrant IV and should be observed in more detail. Firstly, one immediately notes that photocatalysts doped with commercially available silver still outperform the one doped with biological silver. Secondly, of all samples in quadrant IV, the ones produced like Rachel's third material (Rachel et al. 2002) with water added for suspending clearly show the best conversion. Nevertheless, the photocatalysts doped with commercially available silver also show fairly good conversion results. Rachel1W converts more than the sample on which it was based, being the reference standard Rachel1. All of the previous findings correspond to the ones of the

ACER. Thirdly, one should note that the relative positions of the samples in the fourth quadrant differ slightly depending on the catalytic quantity chosen.

The remaining question is which of the seven acceptable samples is to be advised. Determining a value K (the permitted cost to improve the effectiveness by one unit) simplifies the reasoning here. When conversion is expressed in percentage, two situations can be distinguished from each other. When K is smaller than 1.14×10^{-3} Rachel1W is the best option, because it is the most right hand sample relatively to the straight line through the origin with slope K, whereas when K is larger than this value, Rachel3W becomes the best option. Figure 20 depicts a straight line through the origin with slope 1.14×10^{-3}. In other words, in the former situation, the straight line with slope K is less steep than the one depicted, in the latter situation, it is more steep. (If K amounts to the threshold value, Rachel1W and Rachel3W are equally appealing and no optimal sample can be determined.) When conversion is expressed in ppmv/g, a similar analysis can be performed. Again two situations can be distinguished from each other. Rachel1W is the optimal photocatalyst when K is smaller than 1.56×10^{-3}. In the other situation, with K larger than this value, Rachel3W is the best option. To verify these findings graphically, study Figure 21, which presents a straight line through the origin with slope 1.56×10^{-3}. (Irrespective of the catalytic quantity used, when K amounts to the threshold value, Rachel1W and Rachel3W are equally appealing and no optimal sample can be determined.) Which K value to choose, depends on personal preference. It is probably for the best to attach more importance to the effectiveness than to costs and to choose K values larger than the above mentioned threshold values because of the uncertainty associated with costs. In this case, Rachel3W turns out to be the optimal photocatalyst.

The findings in case of an acetaldehyde intake level of 175 ppmv can be found in Appendix V.

3.2.1.1.4.3 Sensitivity to kilowatt-hour cost

All samples that have good ACERs and ICERs seem to have something in common. Only a small share of the total costs of these samples derives from the consumption of energy. To prove this statement, the samples are divided in two groups. The first group includes eight samples performing very well. The second group contains all other samples. The share of the total cost of each sample that stems from the consumption of energy is calculated. For each group an average is determined. As Table 6 proves, the samples of group 1 consume less energy than the samples of the second group.

Table 6. Share of total cost of synthetic photocatalysts stemming from consumption of energy

GROUP 1		**GROUP 2**	
Material	$\frac{\text{Energy consumption cost}}{\text{total cost}}$	Material	$\frac{\text{Energy consumption cost}}{\text{total cost}}$
NP1W5h	0.0791	NP1	0.7617
Rachel1W	0.1165	NP1 etched	0.6745
Rachel3W	0.0973	NP3	0.8223
Rachel3W500	0.1008	NPW3	0.8317
Rachel3W500(2)	0.1009	TiO2/SnO2 (190/10)	0.7208
Rachel3 Ag0.5wt%	0.1177	TiO2/SnO2 (180/20)	0.7145
Rachel3 Ag1.0wt%	0.1168	TiO2/SnO2 (160/40)	0.7029
Rachel3 Ag1.5wt%	0.1148	TiO2/SnO2 (140/60)	0.6923
		Rachel1	0.5786
		Rachel3	0.5850
		Sonowane	0.6216
		Lim	0.1498
		Lim5h	0.1809
		Rachel3 Bio-Ag0.5wt%	0.1022
Average	**0.1050**	**Average**	**0.5813**

This finding implies that the cost per kilowatt-hour weighs heavily on the ACERs and ICERs of all samples consuming a fair amount of energy (group 2). When the cost per kilowatt-hour diminishes, the total cost of the underperforming samples (group 2) decreases more than the total cost of the other samples (group 1). However, when the cost per kilowatt-hour increases, the opposite is true. Therefore the former situation (decrease of the cost per kilowatt-hour) is very interesting as the differences between both groups become smaller.

So far, a cost per kilowatt-hour of €0.15 has been applied, which is rather high as will be clarified in one of the following sections. Now suppose this cost decreases with 40 % to 0.09 €/kWh. How does a decrease in value of this extremely important cost unit affect the previous analysis?

Table 7 and Figure 22 and 23 represent the ACERs of all synthetic photocatalysts at an acetaldehyde intake level of 110 ppmv.

Table 7. ACERs of synthetic photocatalysts at 110 ppmv acetaldehyde intake and low kilowatt-hour cost

MATERIAL	**MASS IN REACTOR**	**PRICE**	**CONVERSION**	**ACER Conversion (%)**	**CONVERSION**	**ACER Conversion (ppmv/g)**
	g	€	%	€/%	ppmv/g	€/ppmv
NP1	0.1112	0.6967	6.80	0.1024	69.79	0.0898
NP1 etched	0.1746	0.8678	11.62	0.0747	71.04	0.0700
NP1W5h	0.0795	0.2439	33.66	0.0072	501.28	0.0061
NP3	0.0432	0.6163	34.72	0.0178	943.39	0.0151
NPW3	0.1228	0.6056	63.52	0.0095	631.11	0.0078
TiO2/SnO2 (190/10)	0.0979	0.7682	40.56	0.0189	502.27	0.0156
TiO2/SnO2 (180/20)	0.0931	0.7898	32.42	0.0244	421.62	0.0201
TiO2/SnO2 (160/40)	0.0910	0.8332	28.43	0.0293	372.45	0.0246
TiO2/SnO2 (140/60)	0.1001	0.8765	22.42	0.0391	267.00	0.0328
Rachel1	0.0600	0.2770	9.94	0.0279	192.24	0.0240
Rachel1W	0.0654	0.1965	38.12	0.0052	693.66	0.0043
Rachel3	0.0549	0.2731	1.20	0.2282	24.39	0.2040
Rachel3W	0.0507	0.2468	82.71	0.0030	1923.34	0.0025
Rachel3W500	0.0577	0.2492	67.40	0.0037	1362.62	0.0032
Rachel3W500(2)	0.0604	0.2489	64.89	0.0038	1277.61	0.0032
Sonowane	0.0514	0.1614	4.78	0.0337	103.45	0.0303
Lim	0.1322	0.3352	24.61	0.0136	214.05	0.0118
Lim5h	0.0658	0.4117	1.92	0.2141	33.37	0.1875
Rachel3 Ag0.5wt%	0.0628	0.3020	40.66	0.0074	962.47	0.0050
Rachel3 Ag1.0wt%	0.0500	0.2844	42.20	0.0067	798.73	0.0071
Rachel3 Ag1.5wt%	0.0672	0.3068	39.34	0.0078	692.77	0.0066
Rachel3 Bio-Ag0.5wt%	0.0426	0.5419	30.53	0.0177	839.26	0.0152

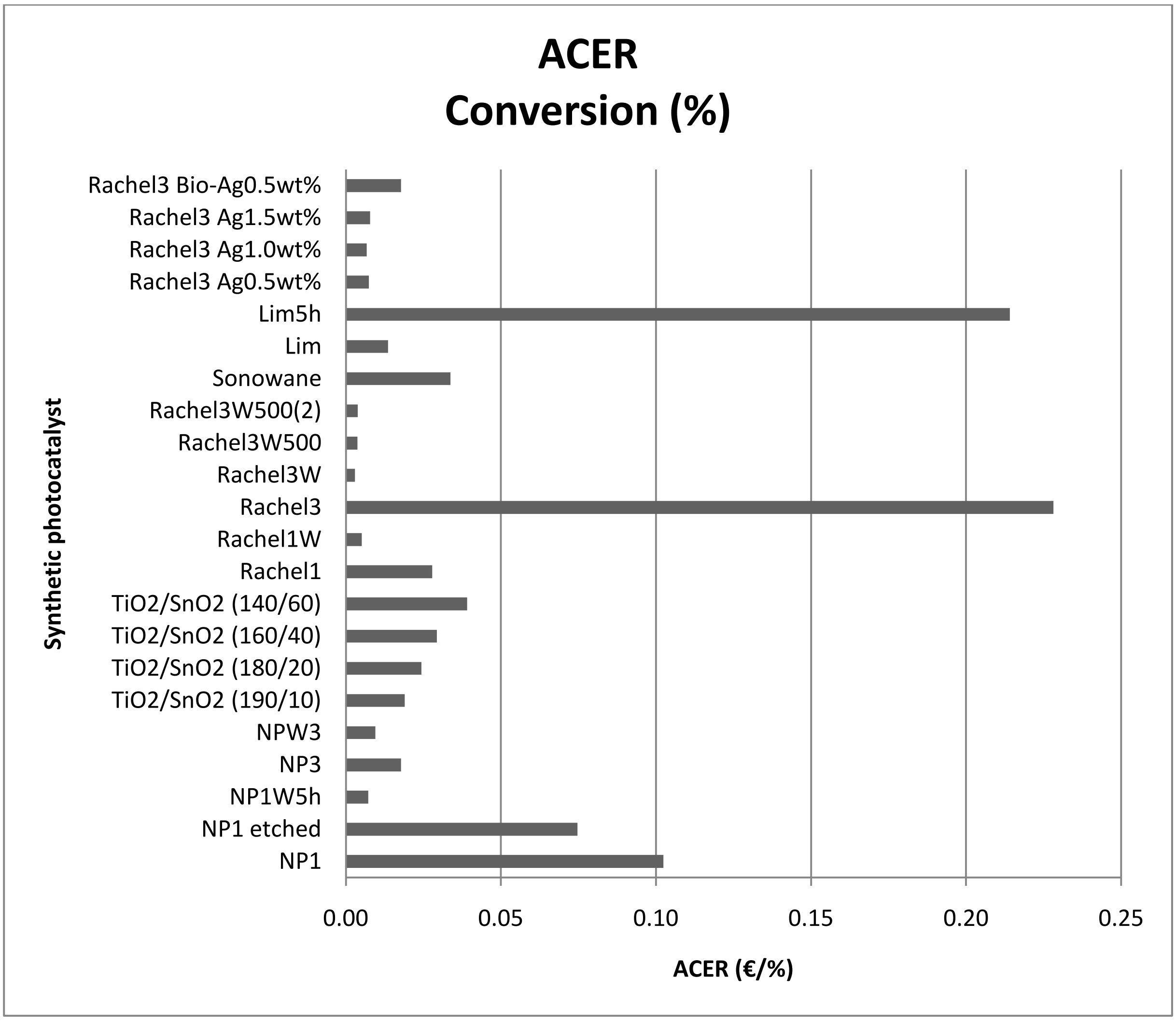

Figure 22. ACERs of synthetic photocatalysts at 110 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in percentage

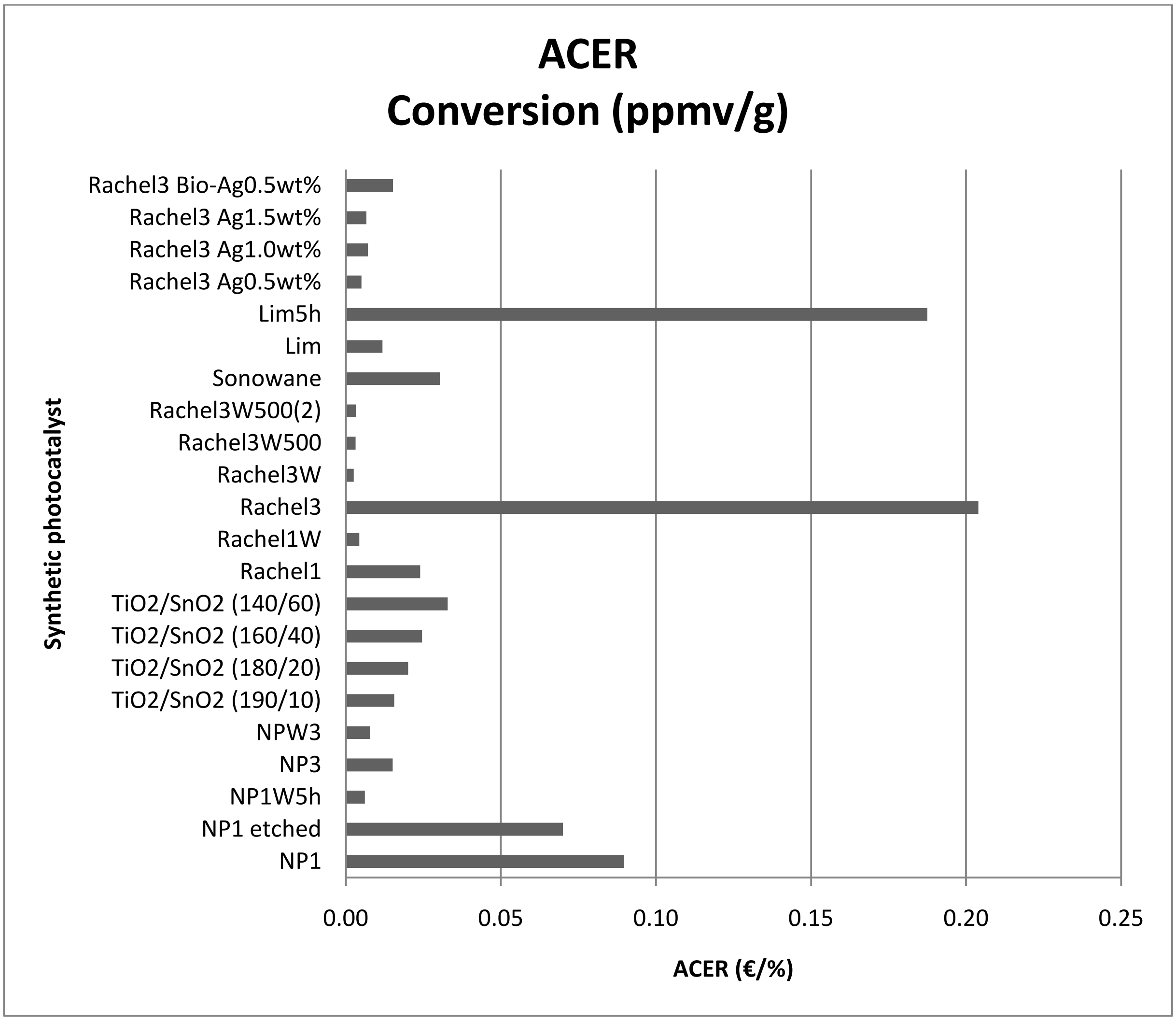

Figure 23. ACERs of synthetic photocatalysts at 110 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in ppmv/g

Although the exact values of the ACERs of all samples changed (the ACERs of both groups do not differ as much anymore), the conclusions that are to be drawn resemble the ones drawn at the higher kilowatt-hour cost.

In this case, Rachel3W's cost will have to rise with more than 23.91 % (to €0.3058) for conversion in percentage and with more than 25.23 % (to €0.3090) for conversion in ppmv/g to alter the findings.

The ACERs in case of an acetaldehyde intake level of 175 ppmv can be found in Appendix VI.

Figure 24 and 25 represent the ICERs of all composite semiconductors at an acetaldehyde intake level of 110 ppmv and a kilowatt-hour cost of €0,09. Once again, NP1 serves as the reference standard.

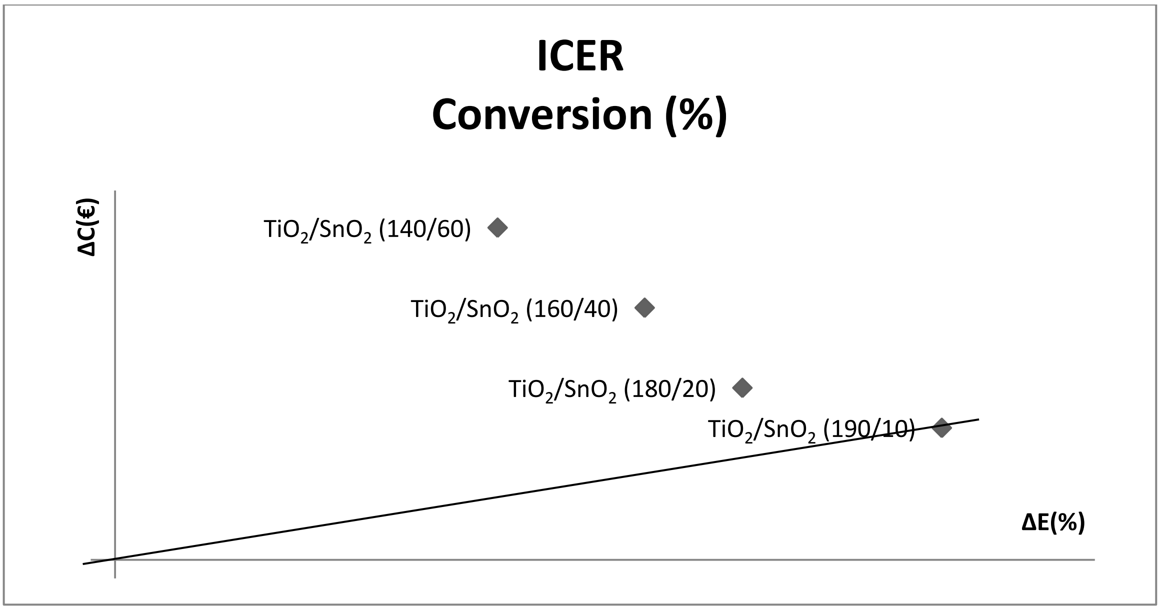

Figure 24. ICERs of synthetic photocatalysts of group 1 at 110 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in percentage

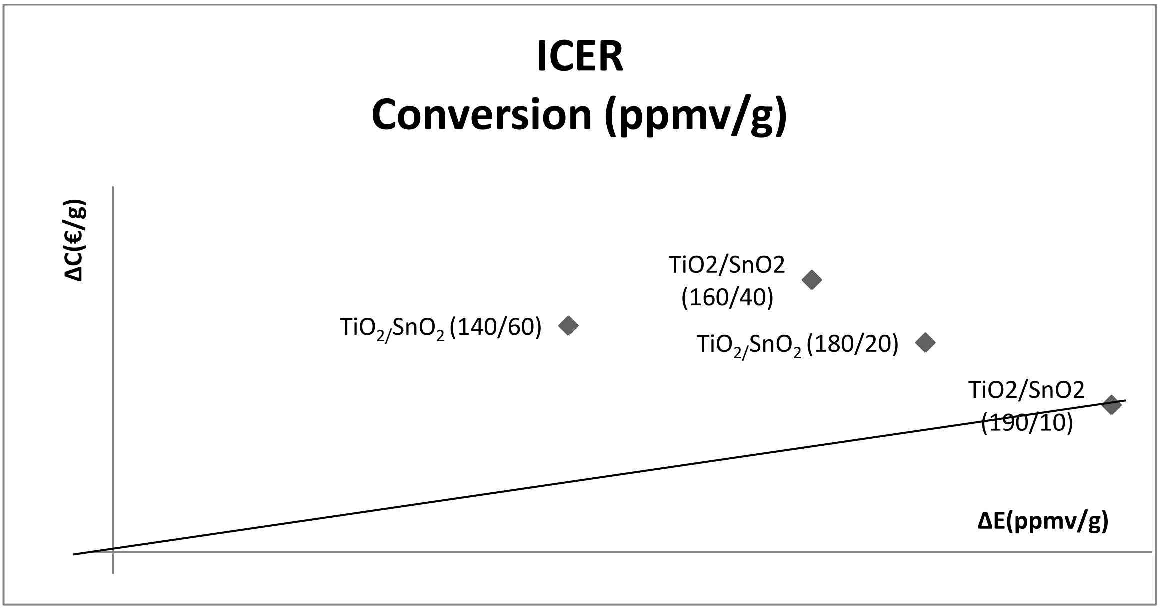

Figure 25. ICERs of synthetic photocatalysts of group 1 at 110 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in ppmv/g

The conclusions drawn in case of the higher kilowatt-hour cost apply here as well. The threshold value for K amounts to 2.12×10^{-3} and 3.66×10^{-3} when expressing conversion in percentage and ppmv/g respectively.

Figure 26 and 27 represent the ICERs of Rachel1W, Rachel3, Rachel3W, Rachel3W500, Rachel3W500(2), Sonowane, Lim5h and all photocatalysts doped with silver at an acetaldehyde intake level of 110 ppmv and a kilowatt-hour cost of €0,09. Once again, Rachel1 serves as the reference standard.

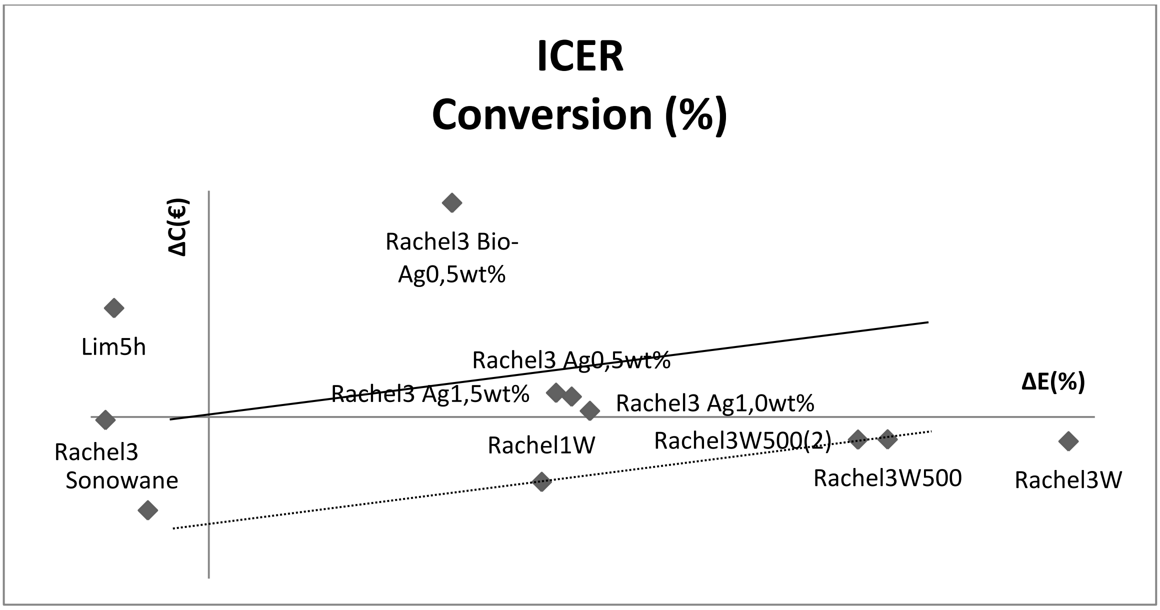

Figure 26. ICERs of synthetic photocatalysts of group 2 at 110 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in percentage

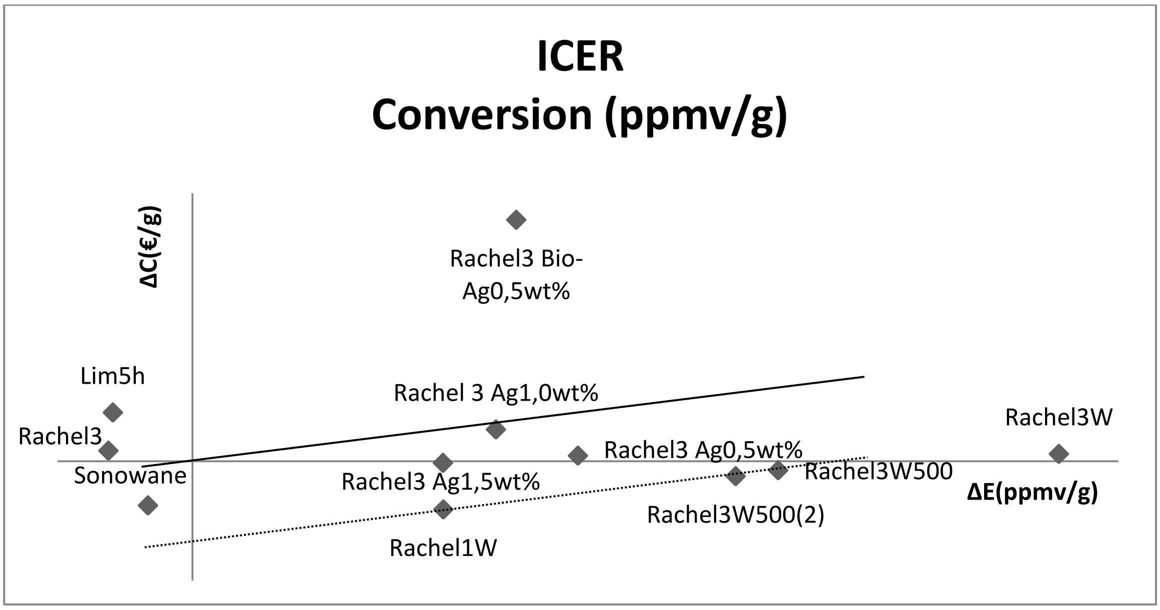

Figure 27. ICERs of synthetic photocatalysts of group 2 at 110 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in ppmv/g

One can immediately note that several samples that used to be in quadrant IV moved up to quadrant I in which a K value has to be chosen to determine whether the photocatalysts are appealing or not. This could be expected because costs associated with the consumption of energy previously weighed rather heavily on Rachel1 that acts as the reference standard. The lower cost per kilowatt-hour results in smaller differences between Rachel1's cost and the costs of all other samples of group 2 and thus lowers the vertical spread between the samples. Three samples are located in quadrant I irrespective of the chosen catalytic quantity (Rachel1W, Rachel3W500 and Rachel3W500(2)) and will therefore be studied further. To determine which of those three samples is the optimal one, a value K can be determined. When conversion is expressed in percentage, one should opt for Rachel1 if K is smaller than $1{,}80 \times 10^{-3}$. If K is larger than this threshold value, Rachel3W500 becomes the optimal photocatalytic material. (Rachel1 and Rachel3W500 are equally appealing when K amounts to the threshold value.) When conversion is expressed in ppmv/g, Rachel1 is advisable if K is smaller than $1{,}91 \times 10^{-3}$, Rachel3W500(2) if K falls between $1{,}91 \times 10^{-3}$ and $1{,}96 \times 10^{-3}$ and Rachel3W500 if K is larger than $1{,}96 \times 10^{-3}$. (If K amount to exactly $1{,}91 \times 10^{-3}$, Rachel1 and Rachel3W500(2) are both advisable. A K value equal to $1{,}96 \times 10^{-3}$ results in a tie between Rachel3W500 and Rachel3W500(2).) Straight lines through the origin with slopes equal to the threshold values have been drawn on Figure 26 and 27 to verify the findings. Because Rachel3W500(2) is only advisable when K amounts to a value in a small range, it will not be taken into consideration any further. Two samples remain: Rachel1W and Rachel3W500. Following the reasoning applied when the cost per kilowatt-hour was higher, it is opted to attach more importance to the effectiveness than to the costs of the samples because of the uncertainty associated with costs. The K values are to be chosen above the (largest) thresholds. As a result, Rachel3W500 can be denominated as the optimal photocatalyst.

The ICERs in case of an acetaldehyde intake level of 175 ppmv can be found in Appendix VII.

Although the costs of all samples differ less than when a high cost per kilowatt-hour was applied (because energy consumption weighs less heavily on the total cost of the samples), the results of the CEA do not seem to have changed dramatically. This stresses the robustness of the findings.

3.2.1.2 Titanium dioxide

The technology under investigation applies TiO_2 as a photocatalyst. This is an oxide of titanium that occurs naturally. The size of the titanium supply in the earth affects the price of the semiconductor which in turn affects the quantity supplied of the contemplated technology. As mentioned before, the earth crust consists of approximately 0.62 % of titanium (Shon et al., 2008).

According to Shon et al. (2008), TiO_2 is a material which can be applied in various situations. Firstly, and most importantly, TiO_2 is used as a pigment to deliver whiteness and opacity to several products (i.e. paper, ink, food, cosmetics, paints, coatings…). The material enjoys a high resistance to discoloration under UV light and can be used to sense the oxygen presence in an atmosphere.

Secondly, TiO_2 can also be used to purify water. When photocatalysts are coupled with UV lights they are capable of removing organic pollutants and destroying a variety of bacteria (i.e. Escherichia coli) which can be present in water. Investigators are trying to shift the activity of TiO_2 photocatalysts towards the visible light region. This technology can be recommended because the pollutants are converted into non-toxic wastes which implies that further secondary disposal methods are not required. Moreover, unlike other oxidation technologies which apply expensive oxidation methods, this technology simply uses ambient oxygen.

Thirdly, TiO2 photocatalysts act as the most effective antibacterial agent. Several advantages can be listed. This agent destroys and decomposes the entire bacteria cell even when it is actively propagating or is covered by other cells, it does not deteriorate and is effective during a long period.

Fourthly, to treat (waste) water polluted by organic pollutants, usually absorption on granulated activated carbon and air stripping is used. Unfortunately, society reacted in an anaphoric way and the potential hazard of incineration of organic toxic compounds was dreaded. Photocatalytic semiconductors could offer the solution here by reducing most of these organic compounds to CO_2 and mineral acids.

Fifthly, photodegradation can be applied for the remediation of the marine environment (i.e. in case of oil spills). This topic has not received as much attention as the other ones however, because several factors hinder this research.

Sixthly, TiO_2 photocatalysts are capable of purifying air by converting VOCs in carbon dioxide and water. This opportunity is being exploited in this thesis. Thanks to their modularity, photocatalytic reactors can be incorporated in several air quality devices. It is also possible to coat surfaces with TiO_2 to cleanse air.

Seventhly, TiO_2 coatings are capable of making the surfaces of construction materials self-cleansing and hydrophilic. Several applications of this feature already exist (i.e. self cleaning glass, photocatalytic ceramics, cements and paints) and are still to be created.

Eighthly, soil and sludge polluted by organic contaminants, like the pesticide diuron, can be remediated by means of TiO_2 photocatalysts.

Finally, the nano-sized TiO_2 photocatalytic water-splitting technology can be used to produce hydrogen which is an ideal fuel for the future. Although the technology offers many advantages (i.e. low costs, stable, non corrosive and environmentally friendly), the obtained solar-to-hydrogen energy conversion efficiency is still too low. Therefore, several investigators are looking for ways to improve the efficiency and make the technology economically sound.

The applications expounded above prove that TiO_2 can be useful, either as a pigment or as a photocatalyst, in various situations.

3.2.2 UV LIGHT SOURCE

The technology under investigation uses a TiO_2 semiconductor as a catalyst that is activated under the influence of UV light to degrade acetaldehyde present in indoor air. Obviously, an UV light source is an important production input. When testing the different photocatalytic materials, a Philips Cleo compact S 25 lamp costing €24.5 (without transport costs) and having an expected lifetime of about 800 hours was used which could also be applied when offering the technology under investigation to the end consumer. This type of lamp (which normally is used inside sunbeds), like other types providing UVA light or light with an even smaller wavelength (smaller than 388 nm), is capable of arousing photocatalysis. One should note however that the expected lifetime of the lamp is rather short and could become a problem.

This lamp can be combined, like this was done during the tests of the different photocatalysts, with for example a Vossloh Schwabe L25.346 ballast for a 25 W lamp costing €2 and a Sylvania FS-11 starter costing about €0.67 at the most. The costs of further wiring are negligible.

3.2.3 ENCLOSURE

To prevent the UV light of entering the indoor surroundings, the technology under investigation will have to be enclosed. Once again, the enclosure used during the tests of the different photocatalysts could also be applied when offering the technology to the end consumer. This enclosure was made out of stainless steel and costs about €30.

To make sure (polluted) air is able to reach the photocatalyst in the enclosure, a fan is to be used. Although a fairly simple fan will do, this element of the air-cleaning device will probably be the most expensive one. The features of the fan are to match its utility goal. One would probably like the air in a room to cycle several times through the device. A room of 40 m^2, for example, which is 2.5 m high has a volume of 100 m^3. To realize 3 air changes per hour, a device has to have a delivery power of 300 m^3/h. Next, the fan has to be somewhat heat proof because of the proximity with the UV light source. Furthermore, the fan has to fit, so its dimensions should also be taken into account. Finally, some other technical features (e.g. mean time to failure, pressure, service rating…) are desirable too. An example of a fan that would qualify is the SEPA KA1725HA2BMT which is characterized by a maximum delivery power of 340 m^3/h. It is designed to deal with thermal overload and consists of durable materials like aluminum, magnesium and special steel. This type of fan can be bought at about €47.

3.2.4 LABOUR

Even though automation has become an integral part of society, labour remains a very obvious input into production. The price paid to obtain this input, wage, will have to be kept in mind because it will directly affect the quantity supplied of the technology under investigation. An employee agrees upon a wage with his employer and registers this in an individual contract of employment. This wage has to meet certain minimum norms which exist both at the sectoral (wage scales based on job classification or seniority and sectoral minimum wages both contained in sectoral collective labour agreements closed by Joint Committees) and at the national (a minimum wage contained in national collective labour agreements closed by the National Employment Council) level (Vacature., 2009). The Belgian laws of 5 December 1968 and 3 July 1978 respectively treat contracts of employments and collective labour agreements and are extremely relevant in this context.

Thanks to wage indexation, Belgian wages are linked to the health index which represents the prices of all consumer goods and services (or at least a representative selection of them) with the exception of tobacco, alcohol, gasoline and diesel which are always excluded. The purpose of wage indexation is to safeguard the purchase power against inflation. Wages of civil servants automatically rise with a predetermined percentage each time the trigger index number associated with the health index is exceeded. This system also applies to other payments like unemployment pays, pensions and family allowances. In the private sector, on the other hand, Joint Committees are responsible for the determination of the moment as well as the way of adapting wages

(Vlaamse Dienst voor Arbeidsbemiddeling en Beroepsopleiding, 2008). A wage indexation of 3.9 % is forecasted for 2011 and 2012 (Centrale Raad voor het Bedrijfsleven, 2010).

Moreover, since 1996, a system of preventive wage restraint (law of 26 July 1996) applies which aims at guarding the competitive power of Belgium. Every two years a margin is defined, based on wage increases in The Netherlands, France and Germany, over which Belgian wages can maximally rise (Vacature., 2009). This margin at least equals indexation and conditions with regard to wage scales. For 2011 and 2012, for example, the margin amounts to 5 %; 1.5 in 2011 and 3.4 in 2012. Taking the predicted indexation of 3.9 % into account, perceptible (gross) wage increases can amount to 1.1 % at best (Centrale Raad voor het Bedrijfsleven, 2010).

Globally, wages experience an increasing trend. This can be deducted indirectly from the fact that minimum wages have revived. Employees earning the minimum wage received, on average, 5.7 % more (in real terms) in 2007 than they did at the beginning of this century which represents a substantial gain in their purchasing power. Of course, not all countries experienced this trend. In the Netherlands, minimum wage stagnated, whereas it even decreased in several other countries (like the US and some African countries) during the same period (International Labour Office, 2008).

Data suggest that wages differ across countries (UBS, 2009). This wage gap is often said to originate (at least partially) from differences in productivity (International Labour Office, 2008; Wolf, 2004). Companies should keep this in mind when considering offshore investments. In his working paper, Clemens (2010) holds that large differences in wages across countries exist. According to this paper, three classes of theory which explain the wage gap can be found in literature. The first one claims that spatial differences in earnings are unrelated to differences in productivity of equivalent workers. Obviously, this theory opposes the view mentioned above and even the two remaining theories. The second theory postulates that spatial wage differences are related to productivity differences because, at certain locations, non traded inputs stimulate workers to acquire new human capital on the job. The last theory only differs from the second in that non traded inputs are assumed to augment a worker’s existing human capital here (instead of creating new). Clearly, when planning to expand on the relationship between productivity and wage differences, the course of this paper should be considered.

3.2.5 ENERGY

Energy is an important production input which can be expected to be used during several steps in the production process (e.g. in the production of the photocatalytic materials). It can be delivered to consumers, either private individuals or companies, by electric utilities which express the energy consumption of these clients in terms of the number of kilowatt-hours acquired. The cost of a kilowatt-hour comprises the actual energy price, network tariffs and legal charges (Vlaamse Reguleringsinstantie voor de Elektriciteits- en gasmarkt, 2011).

The actual energy price depends on several factors. Firstly, energy suppliers ask different prices based on electricity costs, their investment costs in green energy and administrative costs to be covered and their predetermined profit margin. Secondly, the actual energy price varies depending on the quantity purchased (i.e. number of kilowatt-hours acquired) with higher acquisitions resulting in lower unit prices. Thirdly, different tariffs apply depending on the exact moment of consumption (i.e. day, night or exclusively night). Finally, indexated energy prices vary over time. Private individuals can even count on a free amount of electricity of which the value will be deducted from the total energy costs (i.e. actual energy price multiplied by number of kilowatt-hours acquired) (Vlaamse Reguleringsinstantie voor de Elektriciteits- en gasmarkt, 2011).

Network tariffs comprise transmission and distribution costs. Transmission costs, on the one hand, are to be paid to compensate Elia for the use of their transmission network. Distribution costs, on the other hand, compensate network controllers for using their network to transport electricity (Vlaamse Reguleringsinstantie voor de Elektriciteits- en gasmarkt, 2011).

Two classes of legal charges can be determined: an energy contribution and a federal contribution. This last class includes: the financing of the Commission for the Regulation of Electricity and Gas [CREG], contributions to the maintenance of nuclear installations, the Kyoto funds and the European Social Fund and the legal charges 'Heating premium' and 'Protected customers' for electricity (Vlaamse Reguleringsinstantie voor de Elektriciteits- en gasmarkt, 2011).

Small professional electricity purchasers with a yearly consumption of 50 MWh (29 MWh at day tariff and 21 MWh at night tariff) pay approximately 0.15 €/kWh which amounts to €7,500 in total (Vlaamse Reguleringsinstantie voor de Elektriciteits- en gasmarkt, 2010). This value was used in the CEA of the synthesized photocatalysts for the computation of the costs of all tested alternatives. It can be argued that the chosen value for consumption is rather low and that the corresponding price per kilowatt-hour weighs heavily on the cost-effectiveness calculations. As a company (and its electricity consumption) grows, the price it has to pay to obtain one kilowatt-hour decreases. So, the applied price in this work probably suits a smaller or a growing company the best. From this point of view, these calculations can be seen as a rather safe starting point perhaps slightly tending more to a worst case than to a best case scenario.

Since 1999 the price per kilowatt-hour has gradually risen in Belgium. The same trend can be seen when inspecting the price for all EU countries starting in 2005 (European Commission, 2011).

Changes in the price of one or several of the production inputs discussed above can be expected to modify the quantity supplied of the technology under investigation.

3.3 STATE OF TECHNOLOGY

3.3.1 THEORETICAL APPROACH

This section discusses the influence the state of technology can have on the quantity supplied of a photocatalyst capable of removing acetaldehyde present in indoor environments. Recall that the state of technology affects the form of the supply function or, in other words, the exact relationship between the independent variables and the dependent one (Lipsey & Chrystal, 2004). But, what causes the state of technology and thus this relationship to change?

The previous question is easier to address by means of an example. Imagine that, in a certain country, the price of an input increases. In the short run, companies using this input will react by producing less and thus controlling costs. In the long run, they will substitute other inputs for the one whose price has increased. Nevertheless, despite these adjustments in inputs, the companies will still be outperformed by foreign competitors which did not experience the price increase in the first place. Therefore, in the very long run, this competitive disadvantage stimulates these companies to engage in research and development in order to reduce the use of the newly expensive input. Processes will be modified until the costs are lower than those experienced by their foreign competitors who did not change their processes because they were not faced with the price increase of the input (Lipsey & Chrystal, 2004).

The previous example clearly demonstrates that companies are restrained by the state of technology in both the short and long run. In the very long run, on the other hand, they can be expected to invent and innovate their way out of trouble caused by increases in their input prices. Because both the substitution of one input for another within the confines of a certain technology (long run) and the technical changes (very long run) are induced by the same things, the latter are often called ‘endogenous technical changes’ (Lipsey & Chrystal, 2004).

Recall that technological changes can affect the quantity supplied of a certain good. A change that decreases production costs, for example, results in a rightward shift of the supply curve (Lipsey & Chrystal, 2004).

3.3.2 *OPEN INNOVATION*

Innovation, which results in technical changes capable of modifying the form of the supply function, can be performed in two distinctly different ways, being closed and open innovation. In the past, most organizations applied the closed innovation model in which research projects are always launched from internal sources. As the projects progress through the process, some are brought to a halt while others receive further attention. Finally, only a limited number of the latter are introduced on the market. Obviously, in this model, projects can only enter and leave the process in one way (Figure 28) (Chesbrough, Vanhaverbeke, & West, 2006).

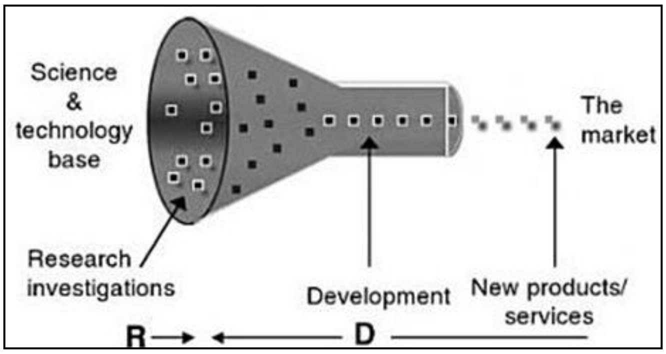

Figure 28. Closed innovation model

Note. From Open innovation - Researching a New Paradigm (p.3), by H.W. Chesbrough, W. Vanhaverbeke, & J. West, 2006, New York: Oxford University Press.

The innovation process is approached differently in the Open Innovation model where research projects can originate both internally and externally and new technology is capable of entering the process at various stages. Furthermore, projects can leave the organization by means of its own channels as well as in other ways. This model clearly differentiates itself from the previous in that ideas can both enter and leave the process in different ways (Figure 29) (Chesbrough et al., 2006).

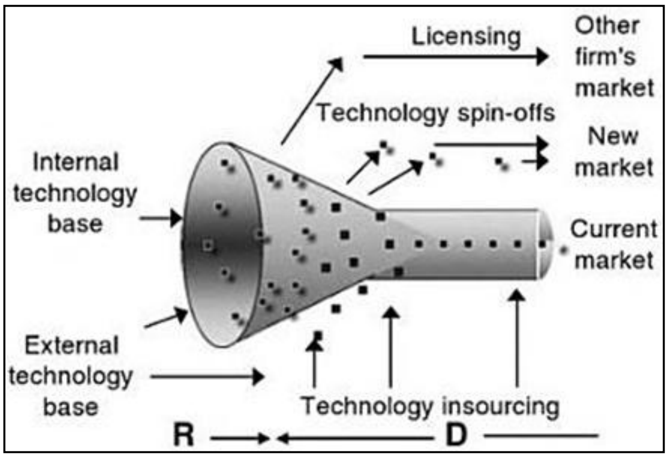

Figure 29. Open innovation model

Note. From Open innovation - Researching a New Paradigm (p.3), by H.W. Chesbrough, W. Vanhaverbeke, & J. West, 2006, New York: Oxford University Press.

3.4 LESSONS LEARNED

This chapter elaborated on the variables affecting the quantity supplied of the technology under investigation. The most obvious ones are the prices of the production inputs. The performance of the photocatalyst is highly dependent on the photocatalytic material used. Considerable differences can be found between the tested materials with regard to their conversion capability. One could opt for the material showing the highest conversion although this could be economically dangerous. Therefore, both the costs and the effects of each sample were compared by means of a CEA. For each material, both the ACER and the ICER were determined. The ACER compares the cost of a certain material with its conversion. The material having the lowest ACER is obviously to be advised. The ICER compares the cost of a photocatalyst relative to a reference standard with this material's conversion relative to this standard. The optimal photocatalyst is chosen by means of the CE plane. Based on both CE ratios, Millenium can be advised as the best commercial photocatalyst. This conclusion holds irrespective of the catalytic quantity and the acetaldehyde intake level chosen. Furthermore, the findings are not sensitive to changes in Millenium's price. For the synthetic materials, the decision is less clear-cut. In general, all samples based on the third preparation clarified by Rachel et al. (2002) in which water was added for suspending performed very well and can be recommended. Once again this conclusion was based both on the ACER and the ICER and can be drawn irrespective of the catalytic quantity and the acetaldehyde intake level chosen. Furthermore, the results do not change when the cost per kilowatt-hour, which weighs heavily on badly performing samples, is lowered.

Next to the photocatalytic material, several other production inputs are relevant. Firstly, a UV light source is needed to activate the photocatalyst. Secondly, some sort of enclosure will be needed to prevent humans against the harmful effects of UV light. Thirdly, a simple fan is to be used to make sure air reaches the photocatalyst. Fourthly, employees will have to be attracted and finally, one will have to consult an electric utility to be provided with energy. As was mentioned above, the prices of all these factors will affect the quantity supplied of the technology under investigation.

CHAPTER IV: CONCLUSIONS

Based on the literature consulted, three methods to reduce indoor air pollution can be determined: source control, ventilation and air-cleaning technologies. One method by itself is not capable of removing all gaseous pollution found indoors. Therefore, combinations are to be made. Source control is always to be applied first because this method can prevent gaseous pollutants of entering indoor environments. Subsequently, one can choose for ventilation (to lower the concentration of pollutants) or air-cleaning technologies (which are end-of-pipe technologies). The more pollution is addressed by means of source control and ventilation, the less remains to be removed by means of air-cleaning technologies, including the photocatalyst under investigation and its direct competitors (gas-phase filters and ozone generators). Although only the prices of the substitutes appear in the demand function, one will have to acknowledge the relevance of looking at the broader competitive environment. Regulative authorities are expected to play an important role in this context, as the numerous examples indicated. They can stimulate the population to employ both indirect competitors while the companies affected by these measures can (more or less) only endure these practices.

The ability to convert acetaldehyde into carbon dioxide and water has been tested for several photocatalytic materials. Some of them are commercially available, others were prepared manually in an academic research centre. To compare the cost and the effects of these materials, a CEA was carried out which is an analysis that perfectly extends the technical research, is fairly simple to perform and is highly comprehensible. For each photocatalyst, both the ACER and ICER were calculated. The ACER compares the cost of a certain material with its conversion (the lower, the more cost-effective), whereas the ICER compares the cost of a photocatalyst relative to a reference standard with the conversion of this material relative to a reference standard (the optimal material is determined by means of a CE plane). Of all commercial photocatalysts examined (P25, TiO_2 Aerolyst, Hombikat, Millenium, P90 and PF2), Millenium ranked first. This conclusion can be made based on the ACERs and ICERs, at both acetaldehyde intake levels, irrespective of the catalytic quantity applied and is not sensitive to fluctuations in Millenium's price. Next, several samples of photocatalytic material were produced manually by following certain preparation methods proposed in scientific literature. The rather disappointing performance of these materials led to the further refinement of these methods. A total of twenty-two samples were tested. Although, this time, the situation was not as clear-cut, it can be concluded that the samples based on the third preparation method of Rachel et al. (2002) with water added for suspending outperform all other samples. Once again, this conclusion holds irrespective of the specific CE ratio consulted, the acetaldehyde intake level present and the catalytic quantity chosen. The results do not change when the cost per kilowatt-hour, which weighs heavily on all badly performing samples, is altered.

The main limitation of this thesis is the fact that the acetaldehyde intake levels applied are higher than the levels which are to be expected in an average indoor environment. As a result, it is difficult to draw conclusions concerning the device on a realistic scale based on the results found at the academic research centre.

Next, several assumptions were made throughout this thesis (underlying economic model, price dependency of all commercial photocatalysts on TiO_2…). It would be very interesting to examine how the results would change when an assumption does not hold.

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APPENDICES

APPENDIX I

ACERS OF COMMERCIAL PHOTOCATALYSTS AT ACETALDEHYDE INTAKE LEVEL OF 175 PPMV

The ACERs of the commercial photocatalysts were also calculated at an acetaldehyde intake level of 175 ppmv. Table I.1 summarizes these findings.

Table I.1. ACERs of commercial photocatalysts at 175 ppmv acetaldehyde intake

MATERIAL	MASS IN REACTOR	PRICE	CONVERSION	ACER Conversion (%)	CONVERSION	ACER Conversion (ppmv/g)
	g	€/g	%	10-6€/%	ppmv/g	10-6€/ppm
P25	0.0501	0.0300	76.28	19.70	2689.90	11.15
TiO2 Aerolyst	0.0487	1.6000	52.34	1488.71	1828.94	874.82
Hombikat	0.0589	0.2476	76.73	190.05	2264.09	109.36
Millenium	0.0500	0.0250	99.89	12.51	3476.70	7.19
P90	0.0654	0.0330	96.67	22.32	2613.49	12.63
PF2	0.0609	0.0900	3.60	1522.39	105.49	853.19

Both tables indicate Millenium as being the most cost-effective alternative (with a combination of the lowest cost and the highest conversion), followed by P25, P90 (which both have a reasonably low cost and rather high conversion) and Hombikat respectively. TiO_2 Aerolyst and PF2 have very high ACERs and will not receive further consideration in this specific context. The latter may not seem surprising since neither of both products was developed to be applied as a photocatalyst. This interpretation can be nuanced however.

The findings can also be represented graphically (Figure I.1 and I.2).

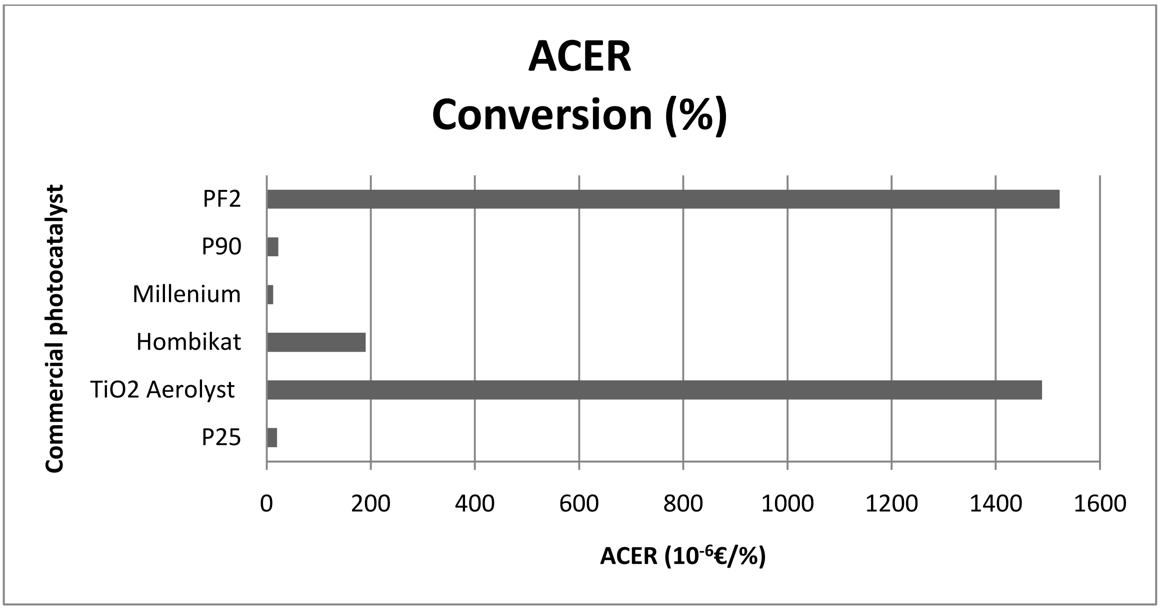

Figure I.1. ACERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in percentage

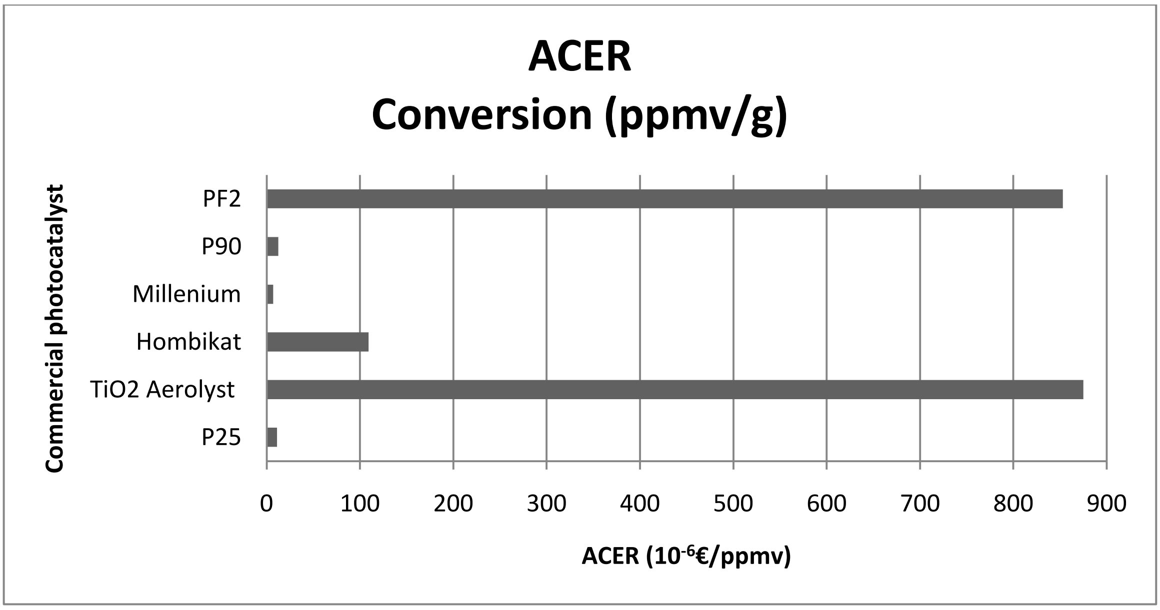

Figure I.2. ACERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in ppmv/g

Clearly, the evaluation of Figure I.1 and I.2 leads to the same conclusion as the one that was drawn above. Once again, it is not very sensitive to price alterations. Millenium’s price will have to rise with 57.46 % (to 39.37 €/mg) for conversion in percentage and with 55.10 % (to 38.78 €/mg) for conversion in ppmv/g to alter the conclusion. In both cases these large price increases will be in favor of P25.

APPENDIX II

ICERS OF COMMERCIAL PHOTOCATALYSTS AT ACETALDEHYDE INTAKE LEVEL OF 175 PPMV

Figure II.1 shows the CE plane of the commercial photocatalysts in case an acetaldehyde intake of 175 ppmv was employed and conversion was expressed in percentage.

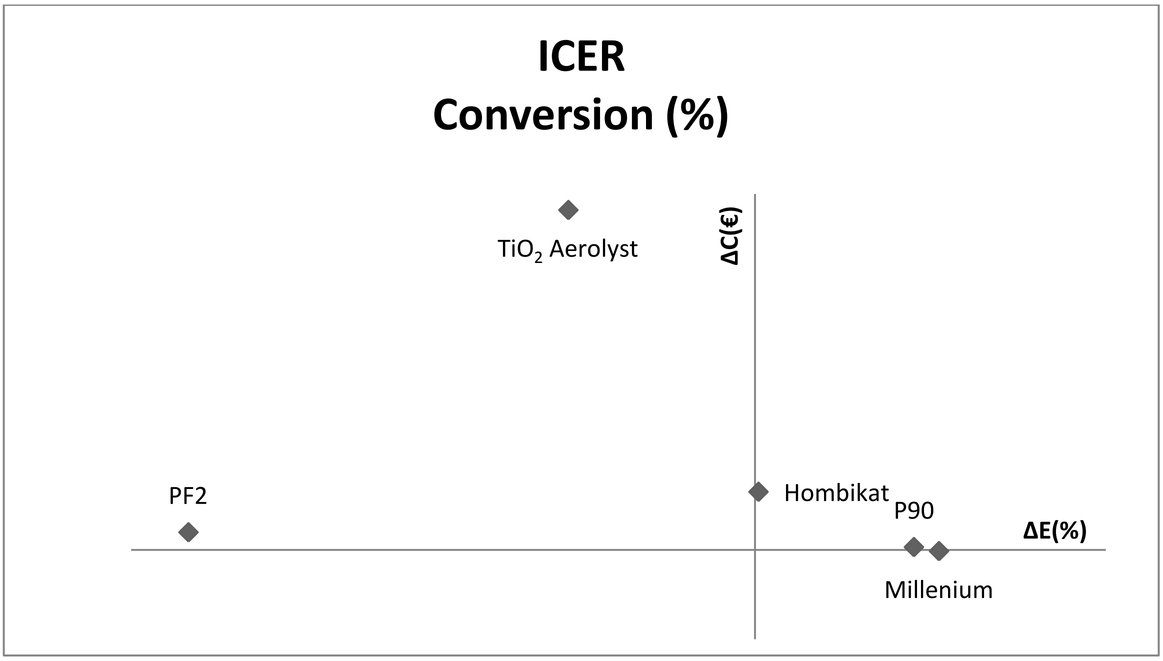

Figure II.1. ICERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in percentage

Although the positions of the different alternative materials in the CE plane have changed somewhat, Figure II.1 leads to the exact same conclusions as Figure 9. Since Millenium shows the best conversion at the lowest cost (compared to all other commercial photocatalysts) (graphically the lowest and most right hand position), Millenium will be the best option independent of the value one sets for K.

This section will have a look at the sensitivity of the results to price fluctuations. Several scenarios could take place.

Scenario A: Obviously, the appropriate calculations lead to exactly the same results that were found when employing an acetaldehyde intake level of 110 ppmv. Millenium's price can increase with the same percentage, being 20.24 %, until the Millenium's sample cost as much as the P25 sample (that is €0.0015). Price growths of (maximally) this percentage will not change the original conclusion. Again, this can be depicted graphically (Figure II.2).

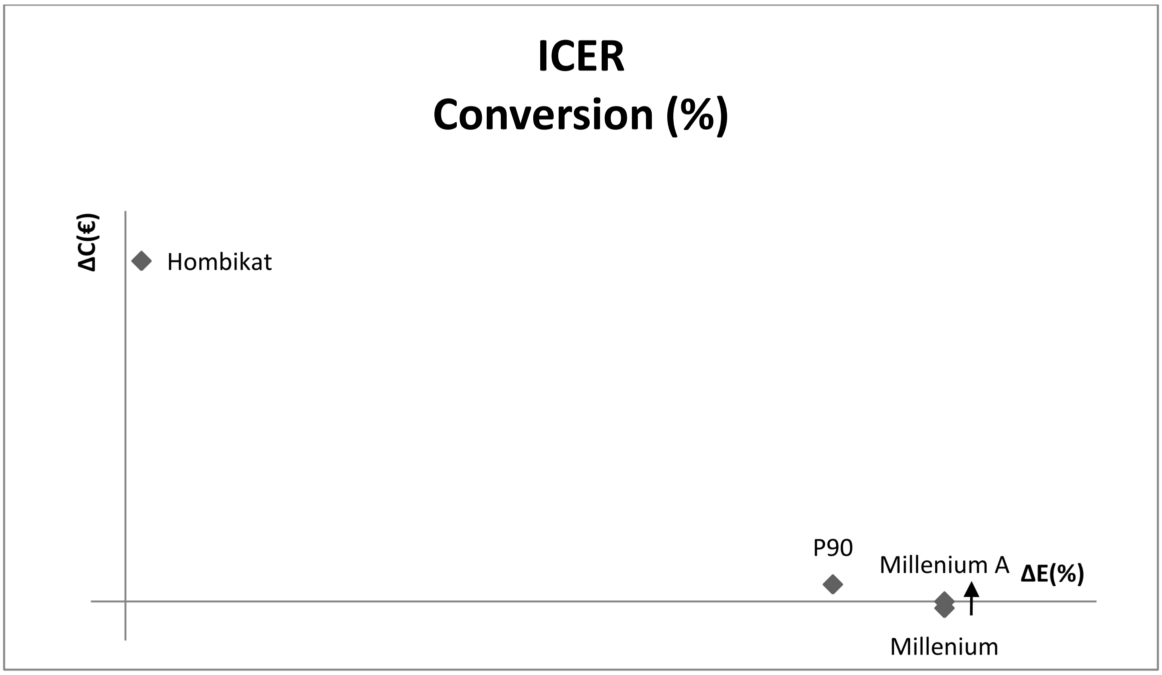

Figure II.2. Sensitivity of ICERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario A

Scenario B: Parallel to the reasoning at an acetaldehyde intake of 110 ppmv, suppose Millenium's price increases with more than 20.24 % (to more than 30.06 €/mg) and K falls between 0 and $3.21\text{x}10^{-5}$. The cost of the Millenium sample would amount to more than €0.0015. The maximum value for K is the slope of the straight line crossing both the origin and P90 and thus equals the ICER of P90. When K is equal to this maximum value and Millenium is situated to the right of the straight line through the origin, it always is a more appealing option than P25, P90 (which are advisable to the same extent) and Hombikat. When K is smaller than the maximum value (but positive) and Millenium is still positioned to the right of the straight line, this photocatalysts again outperforms P25. In this case, both P90 and Hombikat are situated to the left of the straight line which makes them unattractive alternatives. If Millenium would be positioned to the left of the straight line, the latter conclusion also holds for this material. When Millenium costs exactly 45.23 €/mg (with the sample now costing €0.0023) and K amounts to 3.21×10^{-5}, P25, P90 and Millenium would be equally interesting. Hombikat would not be advised. Graphically this scenario can be depicted by an upward shift from Millenium's position on the horizontal axis (scenario A) into a new position on the straight line through the origin and P90 (Figure II.3).

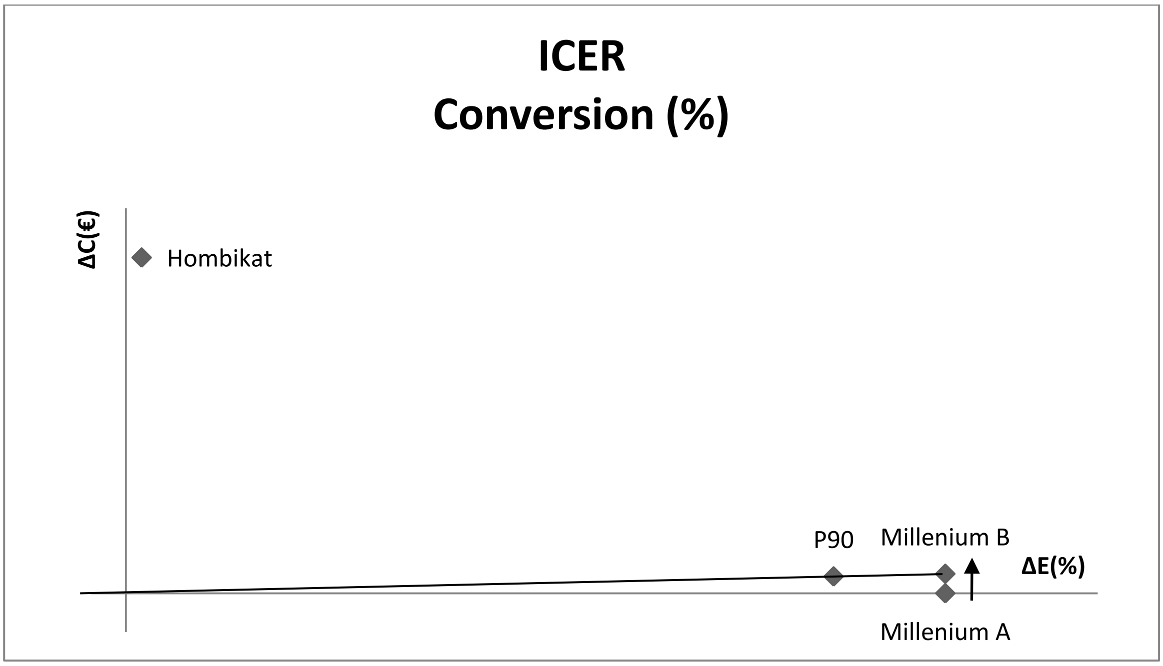

Figure II.3. Sensitivity of ICERs of commercial photocatalysts at 175 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in percentage to increase in Millenium's price – Scenario B

Scenario C: Comparable to the line of thought at an acetaldehyde intake of 110 ppmv, suppose Millenium's price increases more than 80.93 % (to more than 45.23 €/mg) and K falls between 3.21×10^{-5} and 2.87×10^{-2}. The cost of the Millenium sample would amount to more than €0.0023. The maximum value for K is the slope of the straight line crossing both the origin and Hombikat and thus equals the ICER of Hombikat. An example is used to discuss this scenario in further detail. Figure II.4 depicts a straight line through the origin with a slope K chosen from its range (dashed line). In its initial position, Millenium clearly is the best alternative situated the farthest to the right of this dashed line. P90 is the next best alternative, followed by the reference standard P25 and Hombikat (which performs worse than the reference). As Millenium's price starts to rise above 45.23 €/mg, the cost of the sample increases and Millenium moves upward. At a certain instant, it will be situated exactly at the same distance from the dashed line as P90. In graphical terms this means that Millenium is situated on the dotted line (which is parallel to the dashed line and intersect P90). In this case, Millenium and P90 are equally attractive in comparison with P25 while Hombikat can still be left unconsidered. Now imagine Milleniums price would go up some more, increasing the sample’s cost even further. P90 now becomes the best alternative irrespective of Millenium’s position. Firstly, if Millenium is located between the dashed and the dotted line, it is the best alternative next to P90, followed by P25 and Hombikat (which still performs worse than the reference). Secondly, if Millenium is situated on the dashed line, Millenium and P25 are equally appealing next to P90. Once again, Hombikat still underperforms the reference standard and can be forgotten. Finally, if Millenium is situated between the straight line with slope 2.87×10^{-2} and the dashed line, this sample (like Hombikat) is not to be considered any further because it is outperformed by the reference standard P25. P90 remains the advisable option as it is the only sample outperforming P25. The previous conclusion also holds when Millenium is situated on or above the straight line with slope 2.87×10^{-2}. Irrespective of the exact slope of the dashed line (the value chosen for K from the permitted range), a similar approach can be applied to discuss the rank of a certain alternative with regard to the other options.

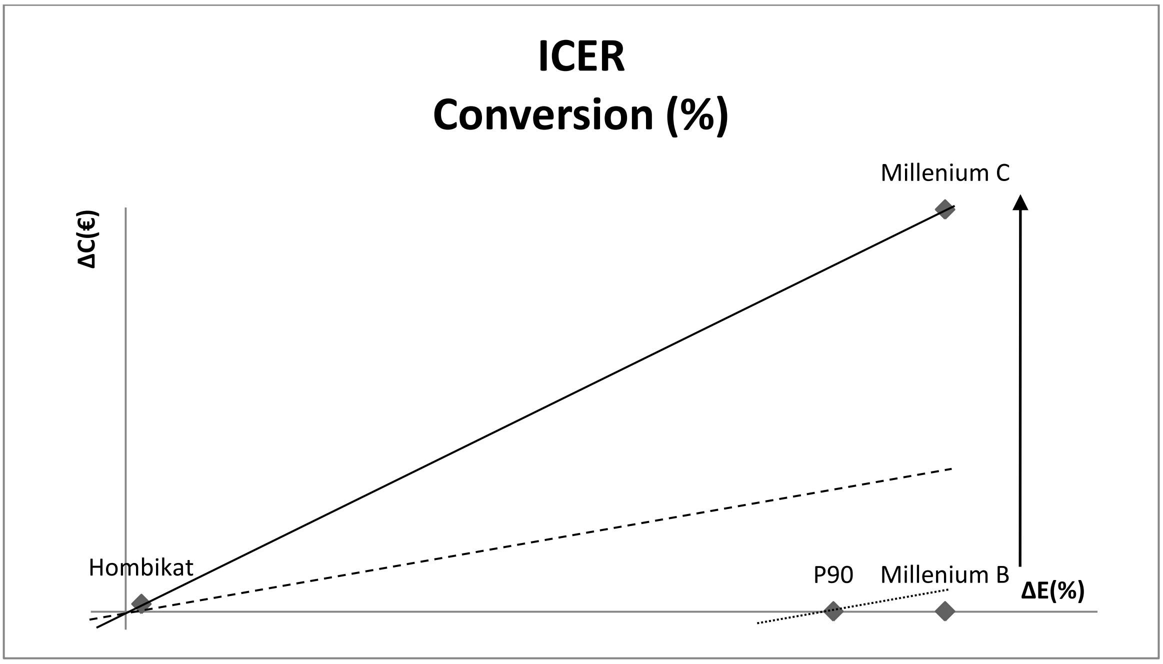

Figure II.4. Sensitivity of ICERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario C(1)

The previous discussion is simplified when K amounts to $2.87\text{x}10^{-2}$. As presented graphically in Figure II.5, the dashed line coincides with the straight line having slope K. In this case, Hombikat is always equally appealing as the reference. As long as the cost of the Millenium sample stays reasonably low (below €0.0944 with Millenium's price amounting to 1,887.81 €/mg) and Millenium is situated below the dotted line which intersects P90 and is parallel to the straight line with slope $2.87\text{x}10^{-2}$ (or the dashed line), Millenium is the best alternative, followed by P90 and by both Hombikat and P25. When Millenium and P90 are both situated on the parallel, they are both equally advisable in comparison with both Hombikat and P25. In this case, Millenium's price amounts to 1,887.81 €/mg and the sample costs €0.0944. When Millenium is located above this dotted line but below the straight line with slope $2.87\text{x}10^{-2}$, P90 is the best option followed by Millenium and both Hombikat and P25. When Millenium forms part of the straight line with slope $2.87\text{x}10^{-2}$, P90 is the only option outperforming the reference standard P25 (and both Millenium and Hombikat having a comparable performance). In this case, Millenium's price amounts to 13,563.77 €/mg and the sample costs €0.6782. When Millenium is situated above the straight line with slope $2.87\text{x}10^{-2}$, it is outperformed by P25 (and of course Hombikat), while P90 remains advisable.

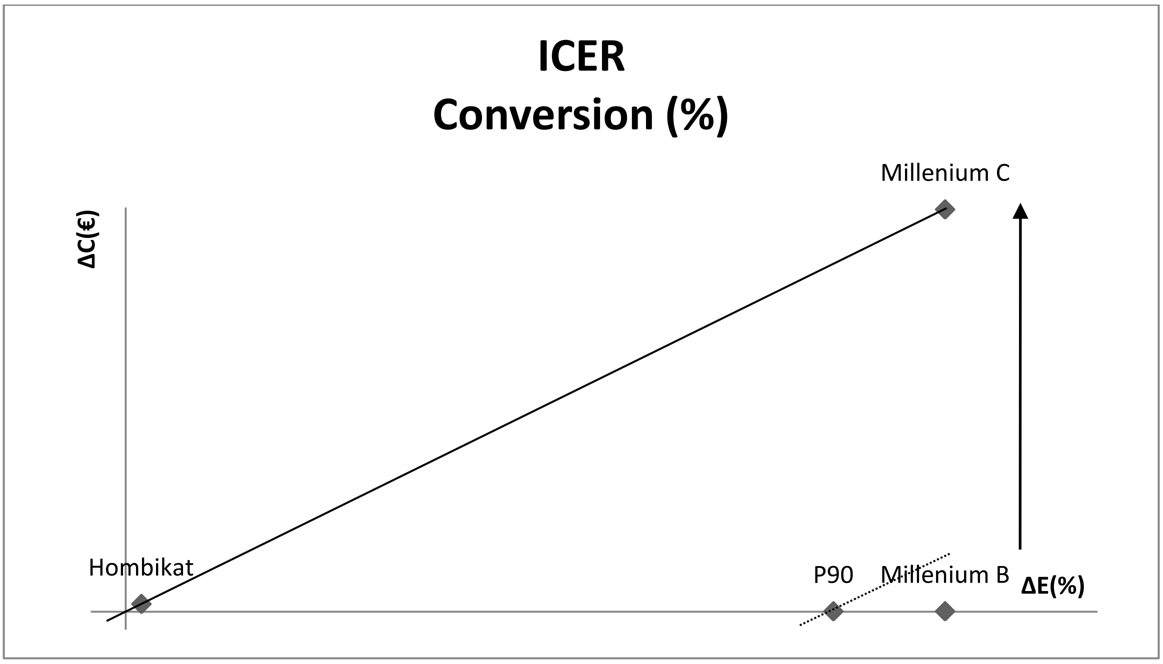

Figure II.5. Sensitivity of ICERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario C(2)

Suppose Millenium's price increases more than 54,155.09 % (to more than 13,563.77 €/mg) and K amounts to more than 6.69×10^{-3}. The cost of the Millenium sample would amount to more than €0.6782. Initially, in Figure II.6, all three alternatives outperform the reference standard P25, with Millenium being the best option, followed by P90 and Hombikat. As Millenium's price starts raising, the cost of that sample also increases. At a certain instant, P90 and Millenium will be equally appealing. In this case, Millenium is situated on the dotted line through P90 and parallel to the straight line through the origin with slope K. As Millenium's price goes up even further, P90 becomes the best alternative, followed by Millenium, Hombikat and P25. When Millenium and Hombikat are both situated on the dashed line having slope K and crossing through Hombikat, P90 is still the best option, but this time it is followed by both Millenium and Hombikat and the reference standard. If Millenium's price rises further without passing the straight line through the origin with slope K, it remains an acceptable option, but it is outperformed by both P90 and Hombikat. When Millenium is situated on the straight line though the origin with slope K, it is equally appealing as the reference standard. All other alternatives, being P90 and Hombikat, perform better. If Millenium's price goes up even further it turns into an inadvisable alternative that is outperformed by the reference standard. On the contrary, both P90 and Hombikat show better results than the reference.

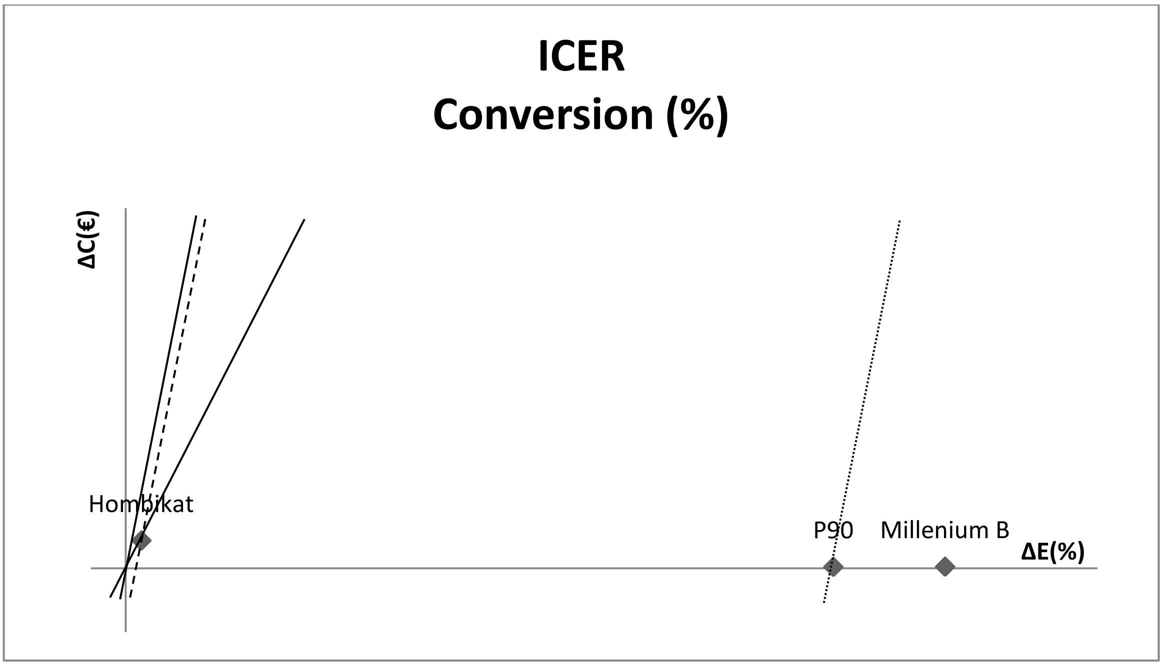

Figure II.6. Sensitivity of ICERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in percentage to increase in Millenium's price – Scenario C(3)

Since, once again, scenario B and C can only take place when Millenium's price increases by more than 20.24 % while all other prices remain unchanged which is not a very realistic situation to expect even in a not very competitive market. Therefore, scenario A will hold and no K value has to be set.

Figure II.7 shows the CE plane of the commercial photocatalysts in case an acetaldehyde intake of 175 ppmv was employed and conversion was expressed in ppmv/g.

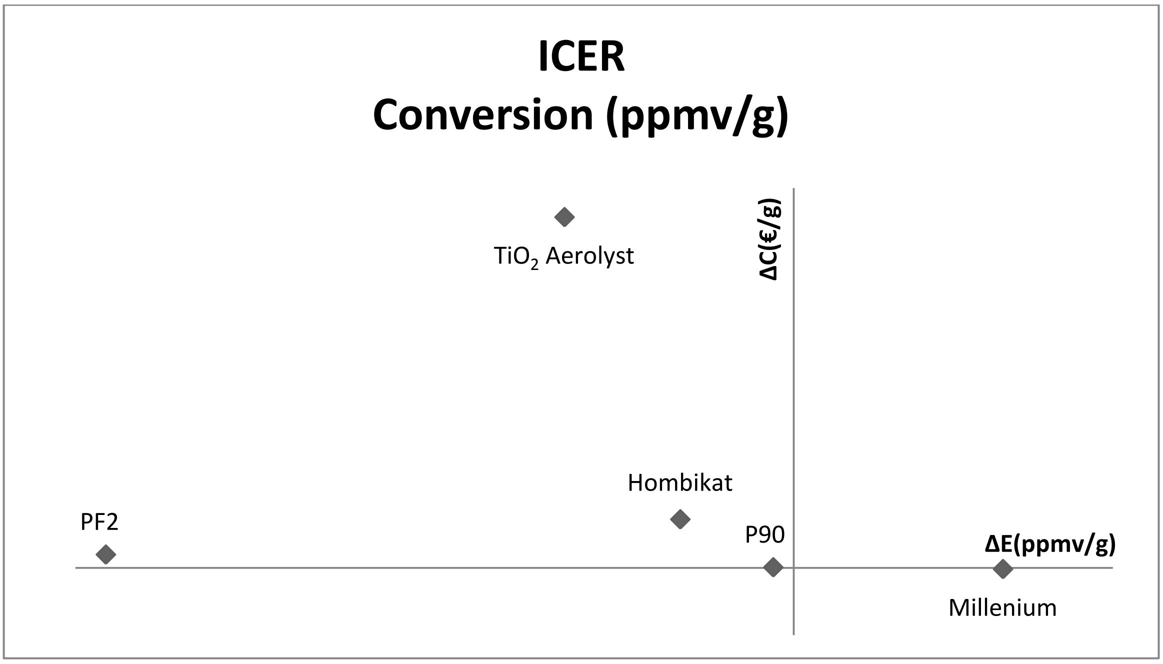

Figure II.7. ICERs of commercial photocatalysts at 175 ppmv acetaldehyde intake with conversion in ppmv/g

Once again, this figure is comparable to Figure 15. A clear distinction can be made between Millenium and all the other products. With the exception of Millenium, all alternatives cost more (in €/g) and convert less (in ppmv/g) than P25.

As was mentioned before, it is necessary to take a look at the sensitivity of the results to price fluctuations. The conclusions which were drawn in case of an acetaldehyde intake level of 110 ppmv are also applicable here. When Millenium's price would rise with more than 20.24 % (and all other prices remain unchanged), the product could move into quadrant I in which case a value for K has to be determined to identify whether Millenium still outperforms P25 being the reference standard. Because such an isolated price increase is not likely to take place, no K value will be set here.

APPENDIX III

COST UNITS OF SYNTHETIC PHOTOCATALYSTS

Table III.1 lists the cost units of all synthetic photocatalysts.

Table III.1. Cost calculations of synthetic photocatalysts

NP1				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
16.944	60.0000	isopropanol	0.083926	0.083926
16.944	10.0000	titanium isopropoxide	0.055124	0.055124
16.944	3.0000	distilled water	0.000144	0.000144
1.000	16.7300	ethanol	0.089506	0.089506
3.000	ultrasonification bath	30min	0.001200	0.000720
16.944	stir	1h5min	0.000134	0.000081
16.944	wash (30,0000ml)	ethanol	0.009473	0.009473
169.435	dry	15h at 60°C	0.000708	0.000425
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h46min warming-up and 22h at 550°C	0.750000	0.450000
16.944	centrifuge	20min at 3000rpm	0.000142	0.000085
		Total	**1.002357**	**0.696683**
NP1 etched				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
8.520	60.0000	isopropanol	0.166904	0.166904
8.520	10.0000	titanium isopropoxide	0.109626	0.109626
8.520	3.0000	distilled water	0.000287	0.000287
1.000	16.7300	ethanol	0.089506	0.089506

5.469	0,1300g	KOH	0.000506	0.000506
5.469	250.0000	distilled water	0.000018	0.000018
5.469	warm water bath	25min	0.038399	0.023040
3.000	ultrasonification bath	30min	0.001200	0.000720
8.520	stir	1h5min	0.000267	0.000160
8.520	wash (30,0000ml)	ethanol	0.018838	0.018838
85.199	dry	15h at 60°C	0.001408	0.000845
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h46min warming-up and 22h at 550°C	0.750000	0.450000
8.520	centrifuge	20min at 3000rpm	0.000282	0.000169
		Total	**1.189241**	**0.867818**
NP1W5h				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
17.000	60.0000	isopropanol	0.083647	0.083647
17.000	10.0000	titanium isopropoxide	0.054941	0.054941
17.000	3.0000	distilled water	0.000144	0.000144
1.000	15.2091	ethanol	0.081369	0.081369
1.000	3.0000	distilled water	0.002442	0.002442
3.000	ultrasonification bath	30min	0.001200	0.000720
17.000	stir	1h5min	0.000134	0.000080
17.000	wash (30,0000ml)	ethanol	0.009441	0.009441
170.000	dry	15h at 60°C	0.000706	0.000424
10.000	dry	15h at 60°C	0.012000	0.007200
34.000	calcine	1h46min warming-up and 5h at 550°C	0.005735	0.003441
17.000	centrifuge	20min at 3000rpm	0.000141	0.000085
		Total	**0.251900**	**0.243934**
NP3				

Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
8.145	5.5000	ethanol (>99,5%)	0.009873	0.009873
8.145	65.0000	distilled water	0.006496	0.006496
8.145	5.0000	titanium isopropoxide	0.057339	0.057339
1.000	16.7300	ethanol	0.089506	0.089506
3.000	ultrasonification bath	30min	0.001200	0.000720
8.145	warm-up initial mix	30min to 60°C and 5h at 60°C	0.005525	0.003315
81.446	dry	15h at 50°C	0.001473	0.000884
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h36min warming-up and 22h at 500°C	0.735000	0.441000
		Total	**0.918412**	**0.616333**
NPW3				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
8.707	5.5000	ethanol (>99,5%)	0.009235	0.009235
8.707	65.0000	distilled water	0.006077	0.006077
8.707	5.0000	titanium isopropoxide	0.053633	0.053633
1.000	15.2091	ethanol	0.081369	0.081369
1.000	3.0000	distilled water	0.002442	0.002442
3.000	ultrasonification bath	30min	0.001200	0.000720
8.707	warm-up initial mix	30min to 60°C and 5h at 60°C	0.005168	0.003101
87.073	dry	15h at 50°C	0.001378	0.000827
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h36min warming-up and 22h at 500°C	0.735000	0.441000
		Total	**0.907502**	**0.605603**
TiO2/SnO2 (190/10)				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**

13.421	60.0000	isopropanol	0.105953	0.105953
13.421	10.0000	titanium isopropoxide	0.069592	0.069592
13.421	3.0000	distilled water	0.000182	0.000182
1.000	16.7300	ethanol	0.089506	0.089506
3.000	ultrasonification bath	30min	0.001200	0.000720
13.421	stir	1h5min	0.000170	0.000102
13.421	wash (30,0000ml)	ethanol	0.011959	0.011959
134.211	dry	15h at 60°C	0.000894	0.000536
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h46min warming-up and 22h at 550°C	0.750000	0.450000
13.421	centrifuge	20min at 3000rpm	0.000179	0.000107
45.000	4,0000g	SnCl4.5H2O	0.018039	0.018039
45.000	30.0000	benzylalcohol	0.004033	0.004033
3.000	ultrasonification bath	30min	0.001200	0.000720
45.000	wash (50,0000ml)	acetone	0.002124	0.002124
45.000	stir	12h at 100°C	0.008000	0.004800
45.000	stir	6h at 110°C	0.004000	0.002400
45.000	centrifuge	1h30min at 4500rpm	0.000320	0.000192
		Total	**1.079350**	**0.768165**
TiO2/SnO2 (180/20)				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
14.167	60.0000	isopropanol	0.100376	0.100376
14.167	10.0000	titanium isopropoxide	0.065929	0.065929
14.167	3.0000	distilled water	0.000172	0.000172
1.000	16.7300	ethanol	0.089506	0.089506
3.000	ultrasonification bath	30min	0.001200	0.000720
14.167	stir	1h5min	0.000161	0.000096
14.167	wash (30,0000ml)	ethanol	0.011329	0.011329

141.667	dry	15h at 60°C	0.000847	0.000508
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h46min warming-up and 22h at 550°C	0.750000	0.450000
14.167	centrifuge	20min at 3000rpm	0.000169	0.000102
22.500	4,0000g	SnCl4.5H2O	0.036078	0.036078
22.500	30.0000	benzylalcohol	0.008065	0.008065
3.000	ultrasonification bath	30min	0.001200	0.000720
22.500	wash (50,0000ml)	acetone	0.004249	0.004249
22.500	stir	12h at 100°C	0.016000	0.009600
22.500	stir	6h at 110°C	0.008000	0.004800
22.500	centrifuge	1h30min at 4500rpm	0.000640	0.000384
		Total	**1.105923**	**0.789836**
TiO2/SnO2 (160/40)				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
15.938	60.0000	isopropanol	0.089224	0.089224
15.938	10.0000	titanium isopropoxide	0.058604	0.058604
15.938	3.0000	distilled water	0.000153	0.000153
1.000	16.7300	ethanol	0.089506	0.089506
3.000	ultrasonification bath	30min	0.001200	0.000720
15.938	stir	1h5min	0.000143	0.000086
15.938	wash (30,0000ml)	ethanol	0.010071	0.010071
159.375	dry	15h at 60°C	0.000753	0.000452
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h46min warming-up and 22h at 550°C	0.750000	0.450000
15.938	centrifuge	20min at 3000rpm	0.000151	0.000090
11.250	4,0000g	SnCl4.5H2O	0.072156	0.072156
11.250	30.0000	benzylalcohol	0.016131	0.016131
3.000	ultrasonification bath	30min	0.001200	0.000720

11.250	wash (50,0000ml)	acetone	0.008498	0.008498
11.250	stir	12h at 100°C	0.032000	0.019200
11.250	stir	6h at 110°C	0.016000	0.009600
11.250	centrifuge	1h30min at 4500rpm	0.001280	0.000768
		Total	**1.159068**	**0.833178**
TiO2/SnO2 (140/60)				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
18.214	60.0000	isopropanol	0.078071	0.078071
18.214	10.0000	titanium isopropoxide	0.051278	0.051278
18.214	3.0000	distilled water	0.000134	0.000134
1.000	16.7300	ethanol	0.089506	0.089506
3.000	ultrasonification bath	30min	0.001200	0.000720
18.214	stir	1h5min	0.000125	0.000075
18.214	wash (30,0000ml)	ethanol	0.008812	0.008812
182.143	dry	15h at 60°C	0.000659	0.000395
10.000	dry	15h at 60°C	0.012000	0.007200
1.000	calcine	1h46min warming-up and 22h at 550°C	0.750000	0.450000
18.214	centrifuge	20min at 3000rpm	0.000132	0.000079
7.500	4,0000g	SnCl4.5H2O	0.108235	0.108235
7.500	30.0000	benzylalcohol	0.024196	0.024196
3.000	ultrasonification bath	30min	0.001200	0.000720
7.500	wash (50,0000ml)	acetone	0.012747	0.012747
7.500	stir	12h at 100°C	0.048000	0.028800
7.500	stir	6h at 110°C	0.024000	0.014400
7.500	centrifuge	1h30min at 4500rpm	0.001920	0.001152
		Total	**1.212213**	**0.876519**
Rachel1				

Division factor	Quantity (mL)	Product	Cost (>€/kWh)	Cost (<€/kWh)
7.667	3.0000	titanium isopropoxide	0.036548	0.036548
7.667	20.0000	isopropanol	0.061826	0.061826
1.000	10.0000	ethanol	0.053500	0.053500
7.667	stir	15min	0.000068	0.000041
10.000	dry	15h at 100°C	0.043500	0.026100
1.000	calcine	1h26min warming-up and 5h at 450°C	0.165000	0.099000
		Total	**0.360442**	**0.277015**
Rachel1W				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
7.674	3.0000	titanium isopropoxide	0.036514	0.036514
7.674	20.0000	isopropanol	0.061769	0.061769
1.000	15.2091	ethanol	0.081369	0.081369
1.000	3.0000	distilled water	0.002442	0.002442
3.000	ultrasonification bath	30min	0.001200	0.000720
7.674	stir	15min	0.000068	0.000041
10.000	dry	15h at 60°C	0.012000	0.007200
15.348	calcine	1h26min warming-up and 5h at 450°C	0.010751	0.006451
		Total	**0.206113**	**0.196505**
Rachel3				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
11.111	4.0000	titanium isopropoxide	0.033624	0.033624
11.111	28.5000	isopropanol	0.060791	0.060791
11.111	0.8330	distilled water	0.000061	0.000061
1.000	10.0000	ethanol	0.053500	0.053500
11.111	stir	30min	0.000095	0.000057

10.000	dry	15h at 100°C	0.043500	0.026100
1.000	calcine	1h26min warming-up and 5h at 450°C	0.165000	0.099000
		Total	**0.356571**	**0.273133**
Rachel3W				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
7.094	4.0000	titanium isopropoxide	0.052662	0.052662
7.094	28.5000	isopropanol	0.095210	0.095210
7.094	0.8330	distilled water	0.000096	0.000096
1.000	15.2091	ethanol	0.081369	0.081369
1.000	3.0000	distilled water	0.002442	0.002442
3.000	ultrasonification bath	30min	0.001200	0.000720
7.094	stir	30min	0.000148	0.000089
10.000	dry	15h at 60°C	0.012000	0.007200
14.189	calcine	1h26min warming-up and 5h at 450°C	0.011629	0.006977
		Total	**0.256755**	**0.246764**
Rachel3W500				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
7.015	4.0000	titanium isopropoxide	0.053258	0.053258
7.015	28.5000	isopropanol	0.096288	0.096288
7.015	0.8330	distilled water	0.000097	0.000097
1.000	15.2091	ethanol	0.081369	0.081369
1.000	3.0000	distilled water	0.002442	0.002442
3.000	ultrasonification bath	30min	0.001200	0.000720
7.015	stir	30min	0.000150	0.000090
10.000	dry	15h at 60°C	0.012000	0.007200
14.030	calcine	1h26min warming-up and 5h at 500°C	0.012830	0.007698
		Total	**0.259632**	**0.249161**

Rachel3W500(2)				
Division factor	Quantity (mL)	Product	Cost (>€/kWh)	Cost (<€/kWh)
7.028	4.0000	titanium isopropoxide	0.053159	0.053159
7.028	28.5000	isopropanol	0.096108	0.096108
7.028	0.8330	distilled water	0.000096	0.000096
1.000	15.2091	ethanol	0.081369	0.081369
1.000	3.0000	distilled water	0.002442	0.002442
3.000	ultrasonification bath	30min	0.001200	0.000720
7.028	stir	30min	0.000149	0.000090
10.000	dry	15h at 60°C	0.012000	0.007200
14.056	calcine	1h36min warming-up and 5h at 500°C	0.012806	0.007684
		Total	**0.259329**	**0.248867**
Sonowane				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
3.571	0,4571g	titanium tetrabutoxide	0.013517	0.013517
3.571	9.5238	distilled water	0.002171	0.002171
3.571	7.1429	waterstofperoxide	0.046580	0.046580
3.571	33.3333	distilled water	0.007597	0.007597
3.571	wash (50,0000ml)	distilled water	0.011396	0.011396
10.000	dry	15h at 100°C	0.043500	0.026100
1.000	calcine	1h16min warming-up and 1h at 400°C	0.090000	0.054000
		Total	**0.214761**	**0.161361**
Lim				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
1.000	1.1000	titanium isopropoxide	0.102740	0.102740
1.000	0.0500	HCl	0.000795	0.000795

1.000	4.1200	ethanol (>99,5%)	0.060234	0.060234
1.000	5.8800	isopropanol	0.139356	0.139356
1.000	stir	5min	0.000175	0.000105
10.000	dry	15min at 100°C	0.000725	0.000435
1.000	calcine	1h36min warming-up and 30min at 500°C	0.052500	0.031500
		Total	**0.356525**	**0.335165**
Lim5h				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
1.000	1.1000	titanium isopropoxide	0.102740	0.102740
1.000	0.0500	HCl	0.000795	0.000795
1.000	4.1200	ethanol (>99,5%)	0.060234	0.060234
1.000	5.8800	isopropanol	0.139356	0.139356
1.000	stir	5min	0.000175	0.000105
10.000	dry	15min at 100°C	0.000725	0.000435
1.000	calcine	1h36min warming-up and 5h at 500°C	0.180000	0.108000
		Total	**0.484025**	**0.411665**
Rachel3 Ag0.5wt%				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
10.951	8.0000	titanium isopropoxide	0.068232	0.068232
10.951	57.0000	isopropanol	0.123359	0.123359
10.951	1.6660	distilled water	0.000124	0.000124
10.951	0,9754g	methanol	0.001134	0.001134
10.951	0,0104g	AgNO3	0.002993	0.002993
10.951	stir	1h	0.000192	0.000115
10.951	UV exposure	3h	0.003082	0.001849
10.951	stir	3h	0.000575	0.000345

109.509	dry	48h at 100°C	0.012711	0.007627
21.902	calcine	1h26min warming-up and 5h at 450°C	0.007534	0.004520
1.000	3.0000	distilled water	0.002442	0.002442
1.000	15.2091	ethanol	0.081369	0.081369
3.000	ultrasonification bath	30min	0.001200	0.000720
10.000	dry	15h at 60°C	0.012000	0.007200
		Total	**0.316947**	**0.302029**
Rachel3 Ag1.0wt%				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
12.190	8.0000	titanium isopropoxide	0.061298	0.061298
12.190	57.0000	isopropanol	0.110824	0.110824
12.190	1.6660	distilled water	0.000111	0.000111
12.190	1,9509g	methanol	0.002037	0.002037
12.190	0,0208g	AgNO3	0.005379	0.005379
12.190	stir	1h	0.000172	0.000103
12.190	UV exposure	3h	0.002769	0.001661
12.190	stir	3h	0.000517	0.000310
121.896	dry	48h bij 100°C	0.011420	0.006852
24.379	calcine	1h26min warming-up and 5h at 450°C	0.006768	0.004061
1.000	3.0000	distilled water	0.002442	0.002442
1.000	15.2091	ethanol	0.081369	0.081369
3.000	ultrasonification bath	30min	0.001200	0.000720
10.000	dry	15h at 60°C	0.012000	0.007200
		Total	**0.298306**	**0.284368**
Rachel3 Ag1.5wt%				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
11.126	8.0000	titanium isopropoxide	0.067160	0.067160

11.126	57.0000	isopropanol	0.121421	0.121421
11.126	1.6660	distilled water	0.000122	0.000122
11.126	2,9263g	methanol	0.003348	0.003348
11.126	0,0311g	AgNO3	0.008811	0.008811
11.126	stir	1h	0.000189	0.000113
11.126	UV exposure	3h	0.003034	0.001820
11.126	stir	3h	0.000566	0.000340
111.258	dry	48h at 100°C	0.012512	0.007507
22.252	calcine	1h26min warming-up and 5h at 450°C	0.007415	0.004449
1.000	3.0000	distilled water	0.002442	0.002442
1.000	15.2091	ethanol	0.081369	0.081369
3.000	ultrasonification bath	30min	0.001200	0.000720
10.000	dry	15h at 60°C	0.012000	0.007200
		Total	**0.321587**	**0.306821**
Rachel3 Bio-Ag0.5wt%				
Division factor	**Quantity (mL)**	**Product**	**Cost (>€/kWh)**	**Cost (<€/kWh)**
5.004	8.0000	titanium isopropoxide	0.149312	0.149312
5.004	57.0000	isopropanol	0.269949	0.269949
5.004	1.6660	distilled water	0.000271	0.000271
5.004	0.5880	bio-Ag	0.003901	0.003901
5.004	stir	30min	0.000210	0.000126
50.043	dry	48h at 100°C	0.027816	0.016690
10.009	calcine	1h26min warming-up and 5h at 450°C	0.016486	0.009892
1.000	3.0000	distilled water	0.002442	0.002442
1.000	15.2091	ethanol	0.081369	0.081369
3.000	ultrasonification bath	30min	0.001200	0.000720
10.000	dry	15h at 60°C	0.012000	0.007200
		Total	**0.564956**	**0.541871**

Table III.1 lists all ‘ingredients’ used and all energy consuming ‘actions’ performed to produce the sample.

For each ‘ingredient’, the quantity used of it is multiplied by its price. The result has to be divided by the division factor when this addition of ingredient contributes to an amount of photocatalytic material that is larger than what is needed to obtain one sample.

The prices of the different ‘ingredients’ were obtained by means of personal communication with the suppliers. Prices can be expected to vary slightly depending on the supplier addressed, the quantity ordered and the moment of purchase. Firstly, for each ‘ingredient’, the regular supplier of the academic research centre was contacted. There will probably be other suppliers willing to deliver at lower prices. Secondly, as to the quantity ordered, the price per liter or per kilo (or as close as possible to this quantity) was used. If this reference quantity would have been higher, lower unit prices could be expected. Finally, calculations prove that samples with high energy consumption costs usually perform badly. Therefore, the sensitivity of the CEA results to changes in the kilowatt-hour cost has been looked at. Because the energy consumption cost was proven to weigh this heavily on the total cost of the samples and this cost unit is relevant for each sample, it was decided to only take the sensitivity of the CEA results to changes in the kilowatt-hour cost into account. In other words, the sensitivity of the CEA results to changes in the prices of the ingredients have not been addressed because they were thought to be inferior. Because of the variations possible in the prices of the ingredients (due to one of the reasons discussed above), it was opted not to mention the suppliers and prices of the products. One can be sure however, that the applied prices represent carefully chosen indicatory values.

For each ‘action’, the energy consumption of the employed device is multiplied by both the high (0.15 €/kWh) and the low kilowatt-hour cost (0.09 €/kWh). Once again, if more than one sample could be treated at once, the result of the previous multiplication has to be divided by the division factor.

Table III.2 represents the energy consumption of the different devices used.

Table III.2. Energy consumption of devices needed to produce synthetic photocatalysts

Device		**Energy consumption**	**Duration**
		kWh	h
stir		0.007	0.5
	100°C (oil bath)	2.400	12.0
	110°C (oil bath)	1.200	6.0
dry	50°C	0.800	15.0
	60°C	0.800	15.0
	100°C	2.900	15.0
calcene	400°C	0.600	1.0
	450°C	1.100	5.0
	500°C	0.350	0.5
	500°C	1.200	5.0
	500°C	4.900	22.0
	550°C	1.300	5.0
	550°C	5.000	22.0
UV exposure		0.300	4.0
centrifuge	3000rpm	0.024	0.5
	4500rpm	0.032	0.5
warm-up initial mix		0.300	5.5
warm water bath	80°C	1.400	7.5
ultrasonification bath		0.024	0.5

APPENDIX IV

ACERS OF SYNTHETIC PHOTOCATALYSTS AT ACETALDEHYDE INTAKE LEVEL OF 175 PPMV

The ACERs of the synthetic photocatalysts were calculated at an acetaldehyde intake level of 175 ppmv and can be found in Table IV.1. Once again, recall that photocatalysts can only be compared without making a considerable error when the mass input of the materials is more or less the same. This is not always the case for the samples of synthetic photocatalytic material. Therefore, when discussing the ACERs, only samples with a more or less equivalent mass input are compared.

Table IV.1. ACERs of synthetic photocatalysts at 175 ppmv acetaldehyde intake and high kilowatt-hour cost

MATERIAL	MASS IN REACTOR	PRICE	CONVER-SION	ACER Conversion (%)	CONVER-SION	ACER Conversion (ppmv/g)
	g	€	%	€/%	ppmv/g	€/ppmv
NP1	0.1112	1.0024	3.93	0.2553	62.35	0.1446
NP1 etched	0.1746	1.1892	7.69	0.1547	75.39	0.0903
NP1W5h	0.0795	0.2519	21.74	0.0116	358.97	0.0088
NP3	0.0432	0.9184	21.90	0.0419	889.86	0.0239
NPW3	0.1228	0.9075	41.08	0.0221	608.55	0.0121
TiO2/SnO2 (190/10)	0.0979	1.0794	26.92	0.0401	494.20	0.0223
TiO2/SnO2 (180/20)	0.0931	1.1059	22.36	0.0495	437.08	0.0272
TiO2/SnO2 (160/40)	0.0910	1.1591	18.81	0.0616	366.55	0.0347
TiO2/SnO2 (140/60)	0.1001	1.2122	16.50	0.0735	294.69	0.0411
Rachel1	0.0600	0.3604	5.47	0.0659	162.69	0.0369
Rachel1W	0.0654	0.2061	26.14	0.0079	717.05	0.0044
Rachel3	0.0549	0.3566	2.75	0.1295	89.65	0.0724
Rachel3W	0.0507	0.2568	59.21	0.0043	2073.01	0.0024
Rachel3W500	0.0577	0.2596	46.00	0.0056	1434.49	0.0031
Rachel3W500(2)	0.0604	0.2593	43.84	0.0059	1287.67	0.0033
Sonowane	0.0514	0.2148	3.00	0.0716	101.33	0.0412
Lim	0.1322	0.3565	16.22	0.0220	212.64	0.0127
Lim5h	0.0658	0.4840	0.50	0.9627	13.50	0.5450
Rachel3 Ag0.5wt%	0.0628	0.3169	27.41	0.0116	983.28	0.0051
Rachel3 Ag1.0wt%	0.0500	0.2983	28.23	0.0106	805.73	0.0074
Rachel3 Ag1.5wt%	0.0672	0.3216	26.42	0.0122	703.30	0.0068
Rachel3 Bio-Ag0.5wt%	0.0426	0.5650	20.39	0.0277	840.04	0.0158

Because of the resemblance between the ACERs at an acetaldehyde intake level of 110 and one of 170 ppmv, the conclusions remain exactly the same.

Figure IV.1 and IV.2 depict the findings by means of histograms.

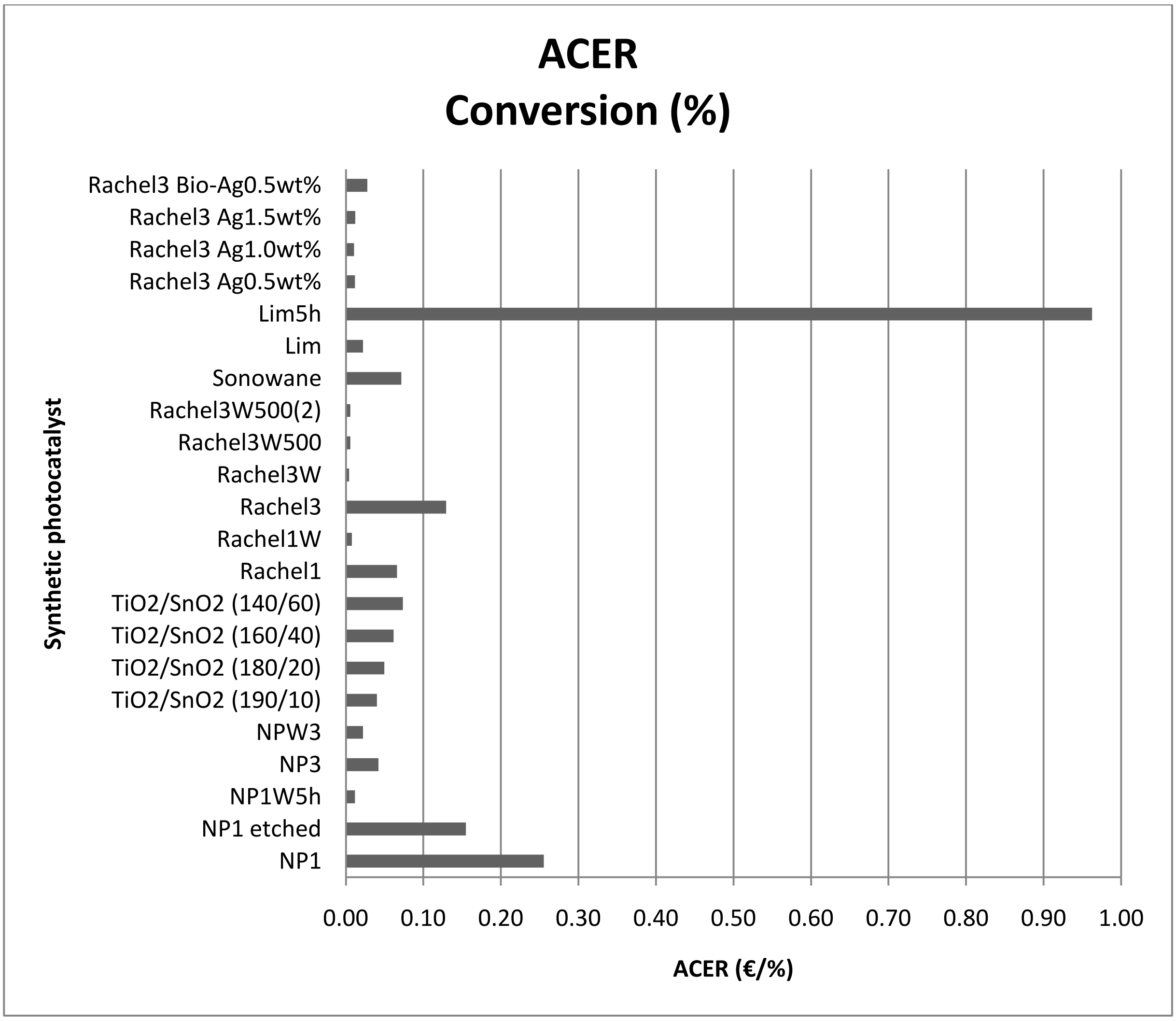

Figure IV.1. ACERs of synthetic photocatalysts at 175 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in percentage

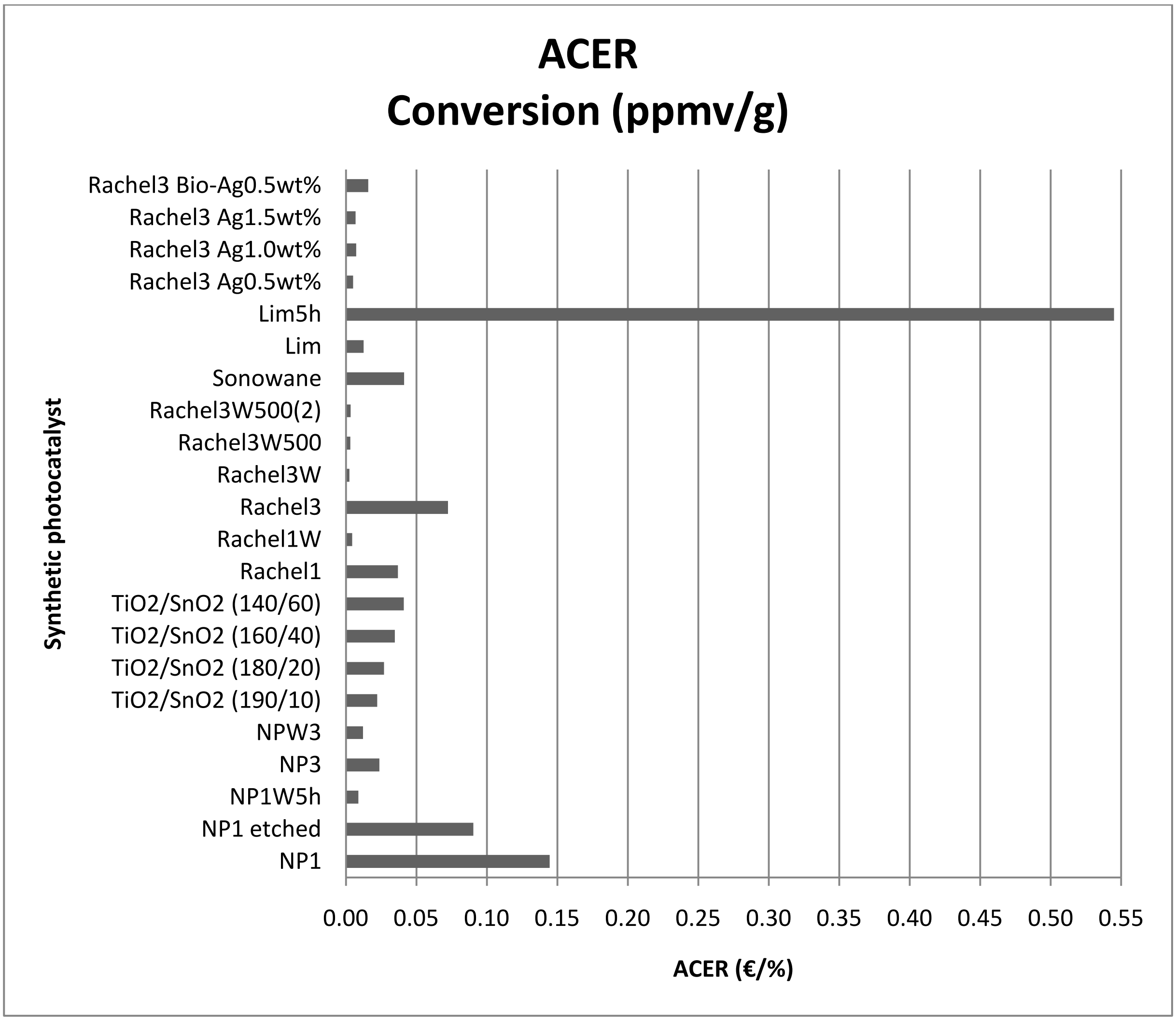

Figure IV.2. ACERs of synthetic photocatalysts at 175 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in ppmv/g

The conclusion drawn above is not very sensitive to price fluctuations. Rachel3W's cost will have to rise with more than 30.15 % (to €0.3342) for conversion in percentage and with more than 28.40 % (to €0.3297) for conversion in ppmv/g to alter the findings described above.

APPENDIX V

ICERS OF SYNTHETIC PHOTOCATALYSTS AT ACETALDEHYDE INTAKE OF 175 PPMV

The ICERs of the synthetic photocatalysts were computed at an acetaldehyde intake level of 175 ppmv for both groups. Figure V.I and V.2 represent the findings for the first group of samples.

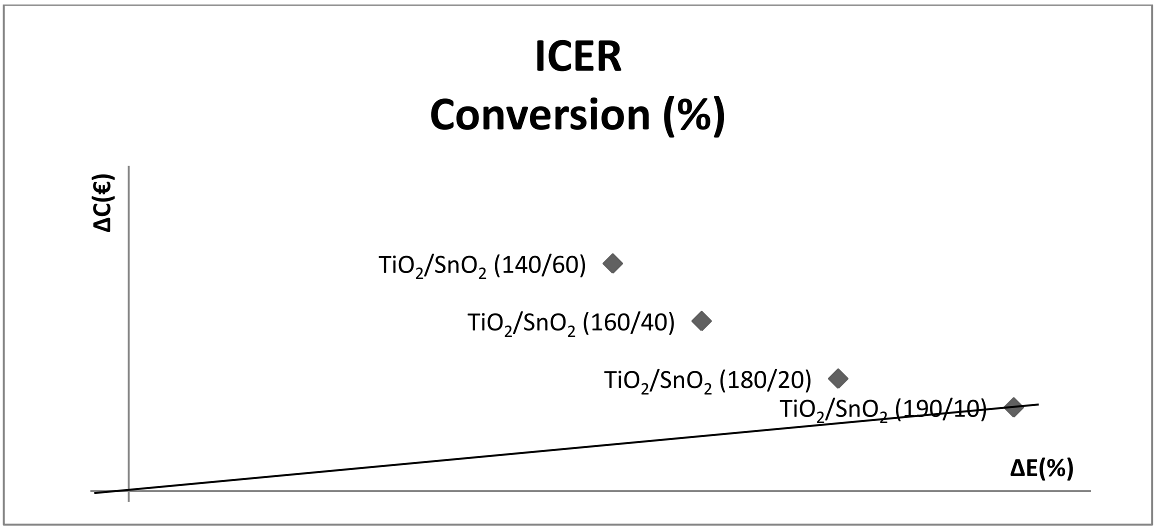

Figure V.1. ICERs of synthetic photocatalysts of group 1 at 175 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in percentage

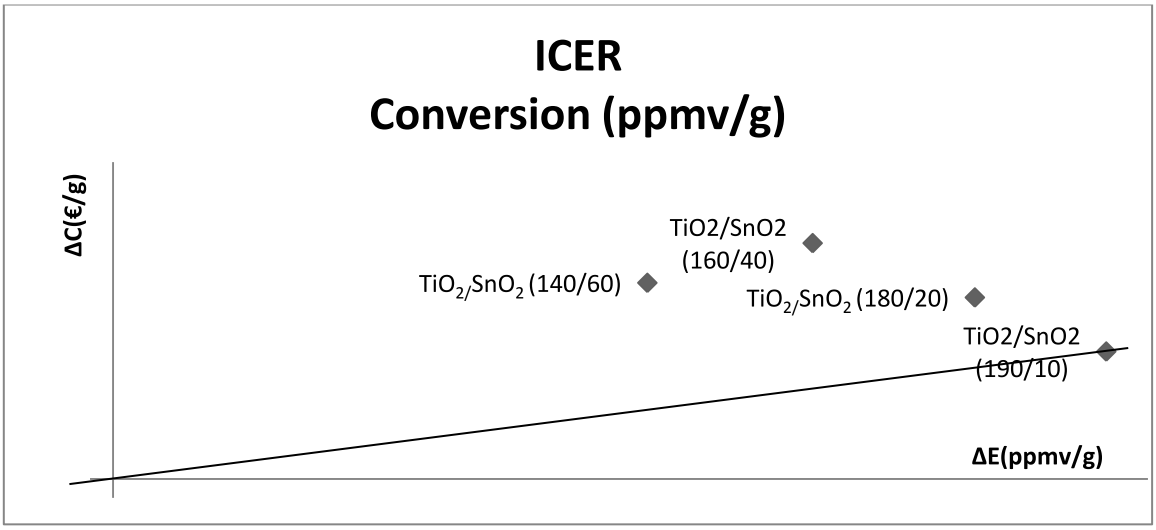

Figure V.2. ICERs of synthetic photocatalysts of group 1 at 110 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in ppmv/g

The conclusions drawn in case of an acetaldehyde intake level of 110 ppmv are applicable here as well. The threshold value for K amounts to $3.35x10^{-3}$ and $4.66x10^{-3}$ when expressing conversion in percentage and ppmv/g respectively.

The same analysis can be performed for all samples belonging to the second group. So, Figure V.3 and V.4 represent the ICERs of these samples at an acetaldehyde intake level of 175 ppmv.

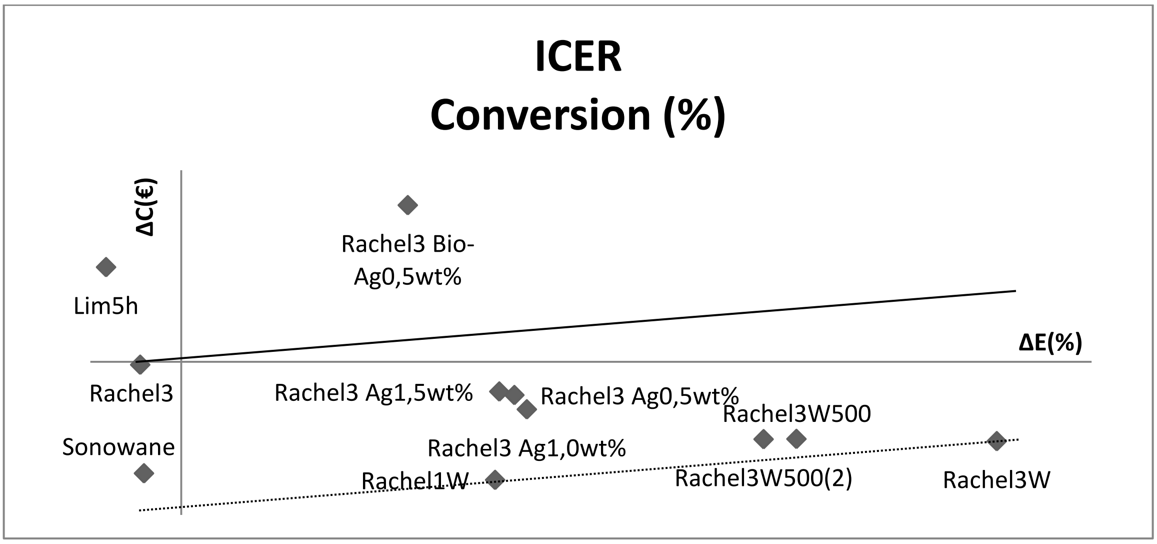

Figure V.3. ICERs of synthetic photocatalysts of group 2 at 175 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in percentage

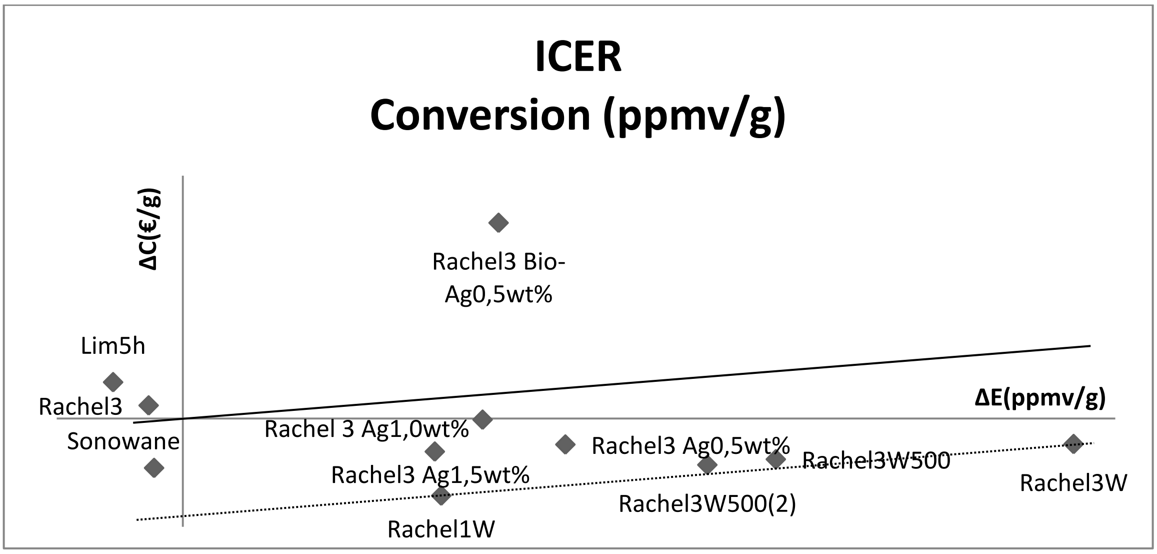

Figure V.4. ICERs of synthetic photocatalysts of group 2 at 175 ppmv acetaldehyde intake and high kilowatt-hour cost with conversion in ppmv/g

One can immediately note the resemblance between these findings and the one at an acetaldehyde intake level of 110 ppmv. Therefore, the exact same conclusions can be drawn for all samples. So, once again, to determine the optimal photocatalyst, two different situations can be distinguished for each catalytic quantity. When conversion is expressed in percentage the threshold value for K amounts to 1.53×10^{-3}. In case conversion is expressed in ppmv/g it amounts to 1.41×10^{-3}. The straight lines through the origin with these slopes are depicted in Figure V.3 and V.4. (Irrespective of the catalytic quantity used, when K amounts to the threshold value, Rachel1W and Rachel3W are equally appealing and no optimal sample can be determined.) Rachel3W remains the most advisable option.

APPENDIX VI

ACERS OF SYNTHETIC PHOTOCATALYSTS AT ACETALDEHYDE INTAKE LEVEL OF 175 PPMV AND LOW KILOWATT-HOUR COST

Table VI.1 and Figure VI.1 and VI.2 represent the ACERs of all synthetic photocatalysts at an acetaldehyde intake level of 175 ppmv.

Table VI.1. ACERs of synthetic photocatalysts at 175 ppmv acetaldehyde intake and low kilowatt-hour cost

MATERIAL	MASS IN REACTOR	PRICE	CONVER-SION	ACER Conversion (%)	CONVER-SION	ACER Conversion (ppmv/g)
	g	€	%	€/%	ppmv/g	€/ppmv
NP1	0.1112	0.6967	3.93	0.1774	62.35	0.1005
NP1 etched	0.1746	0.8678	7.69	0.1129	75.39	0.0659
NP1W5h	0.0795	0.2439	21.74	0.0112	358.97	0.0085
NP3	0.0432	0.6163	21.90	0.0281	889.86	0.0160
NPW3	0.1228	0.6056	41.08	0.0147	608.55	0.0081
TiO2/SnO2 (190/10)	0.0979	0.7682	26.92	0.0285	494.20	0.0159
TiO2/SnO2 (180/20)	0.0931	0.7898	22.36	0.0353	437.08	0.0194
TiO2/SnO2 (160/40)	0.0910	0.8332	18.81	0.0443	366.55	0.0250
TiO2/SnO2 (140/60)	0.1001	0.8765	16.50	0.0531	294.69	0.0297
Rachel1	0.0600	0.2770	5.47	0.0507	162.69	0.0284
Rachel1W	0.0654	0.1965	26.14	0.0075	717.05	0.0042
Rachel3	0.0549	0.2731	2.75	0.0992	89.65	0.0555
Rachel3W	0.0507	0.2468	59.21	0.0042	2073.01	0.0023
Rachel3W500	0.0577	0.2492	46.00	0.0054	1434.49	0.0030
Rachel3W500(2)	0.0604	0.2489	43.84	0.0057	1287.67	0.0032
Sonowane	0.0514	0.1614	3.00	0.0538	101.33	0.0310
Lim	0.1322	0.3352	16.22	0.0207	212.64	0.0119
Lim5h	0.0658	0.4117	0.50	0.8187	13.50	0.4635
Rachel3 Ag0.5wt%	0.0628	0.3020	27.41	0.0110	983.28	0.0049
Rachel3 Ag1.0wt%	0.0500	0.2844	28.23	0.0101	805.73	0.0071
Rachel3 Ag1.5wt%	0.0672	0.3068	26.42	0.0116	703.30	0.0065
Rachel3 Bio-Ag0.5wt%	0.0426	0.5419	20.39	0.0266	840.04	0.0151

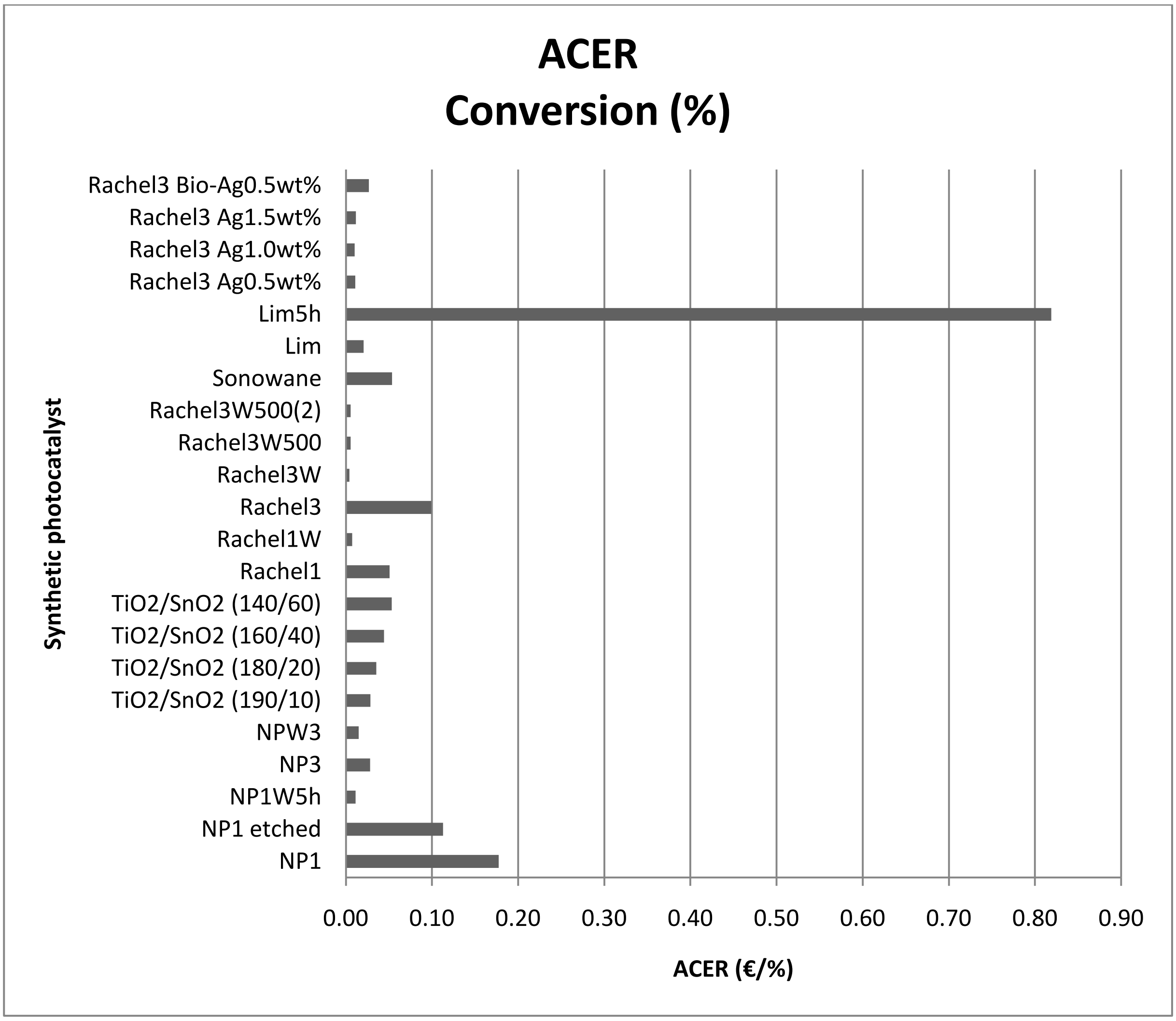

Figure VI.1. ACERs of synthetic photocatalysts at 175 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in percentage

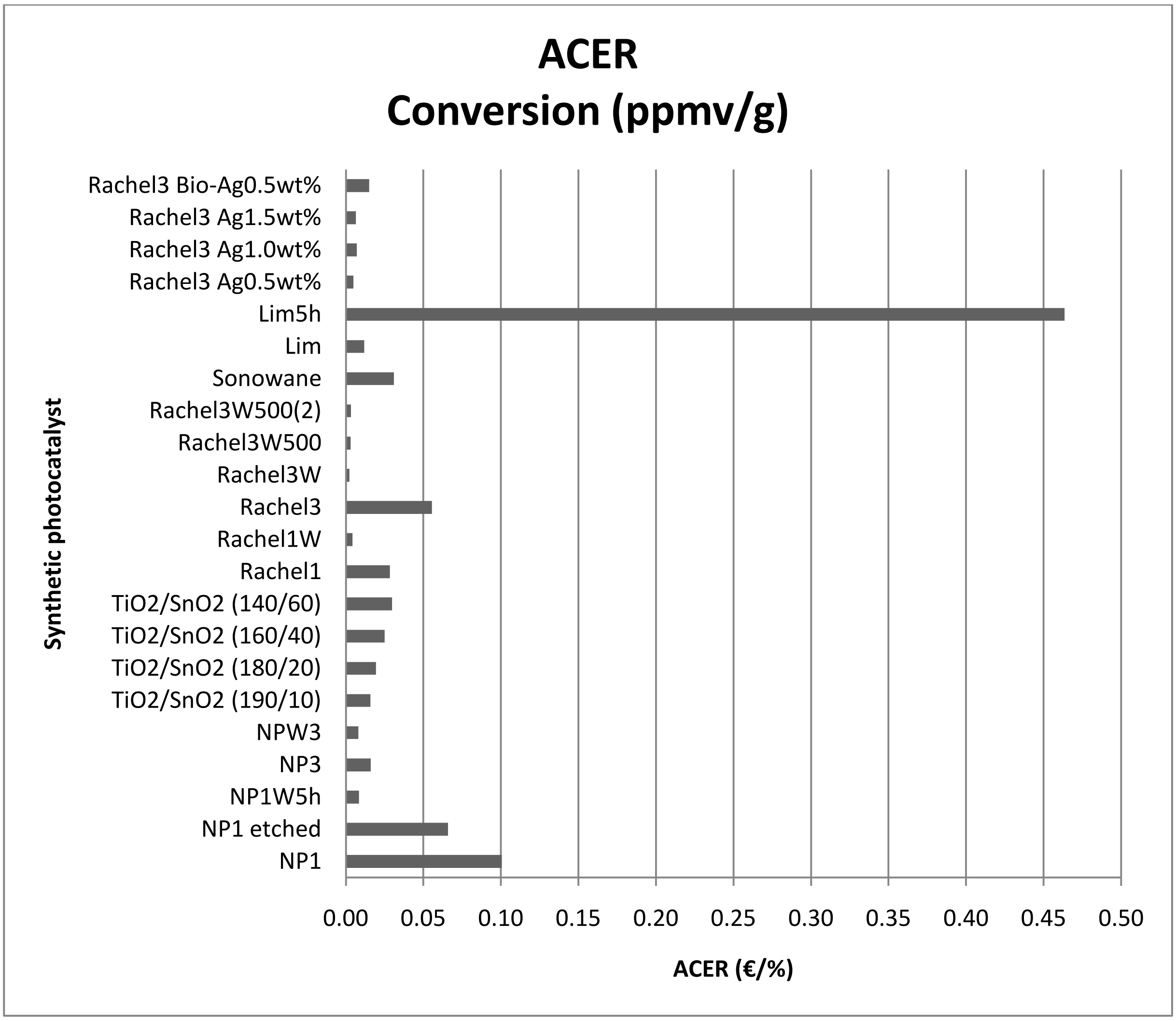

Figure VI.2. ACERs of synthetic photocatalysts at 175 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in ppmv/g

The findings at an acetaldehyde intake level of 110 ppmv also apply here.

In this case, Rachel3W's cost will have to rise with more than 29.95 % (to €0.3207) for conversion in percentage and with more than 28.21 % (to €0.3164) for conversion in ppmv/g to alter the findings.

APPENDIX VII

ICERS OF SYNTHETIC PHOTOCATALYSTS AT ACETALDEHYDE INTAKE LEVEL OF 175 PPMV AND LOW KILOWATT-HOUR COST

Figure VII.1 and VII.2 represent the ICERs of all composite semiconductors at an acetaldehyde intake level of 175 ppmv and a kilowatt-hour cost of €0,09. Once again, NP1 serves as the reference standard.

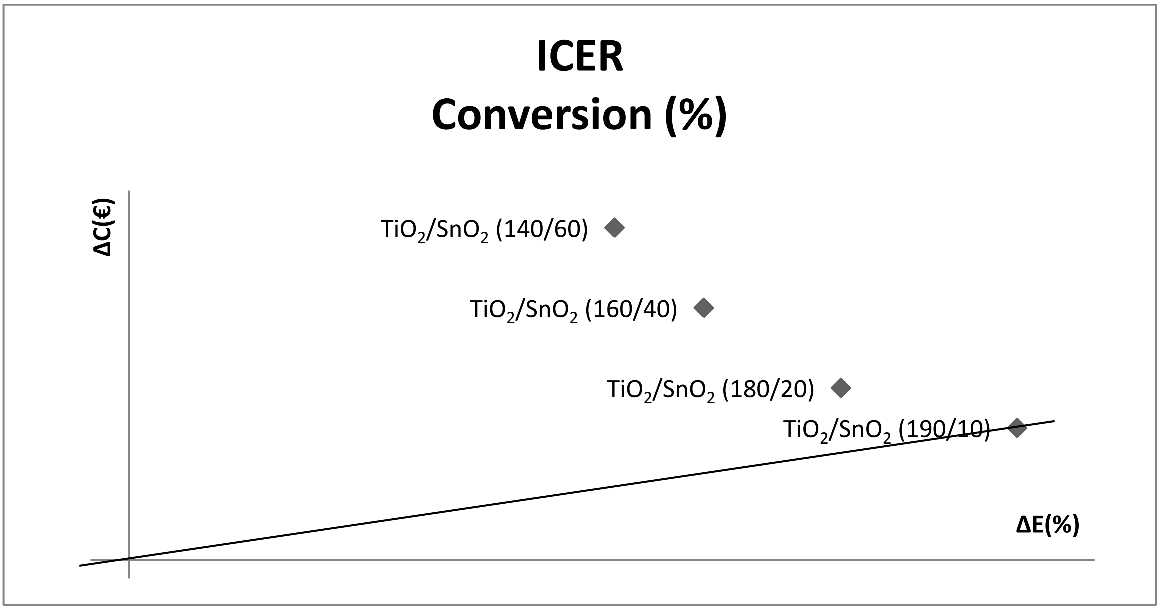

Figure VII.1. ICERs of synthetic photocatalysts of group 1 at 175 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in percentage

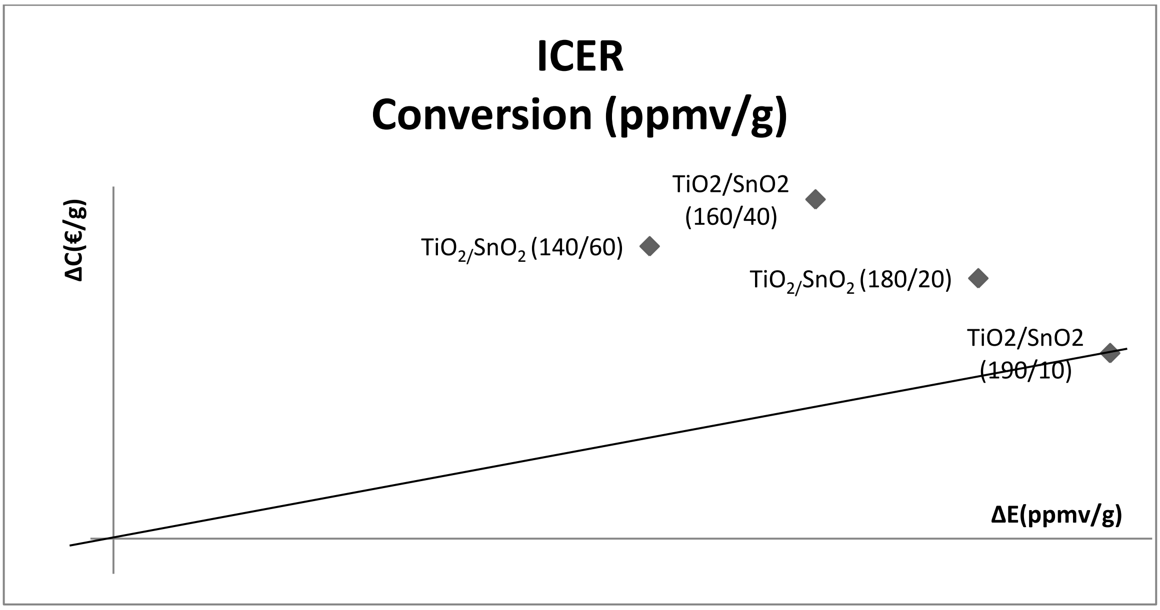

Figure VII.2. ICERs of synthetic photocatalysts of group 1 at 175 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in ppmv/g

Again, the conclusions drawn at an acetaldehyde intake level of 110 ppmv are also applicable here. The threshold value for K amounts to $3.10x10^{-3}$ and $3.66x10^{-3}$ when conversion is expressed in percentage and ppmv/g respectively.

Figure VII.3 and VII.4 represent the ICERs of Rachel1W, Rachel3, Rachel3W, Rachel3W500, Rachel3W500(2), Sonowane, Lim5h and all photocatalysts doped with silver at an acetaldehyde intake level of 175 ppmv and a kilowatt-hour cost of €0,09. Once again, Rachel1 serves as the reference standard.

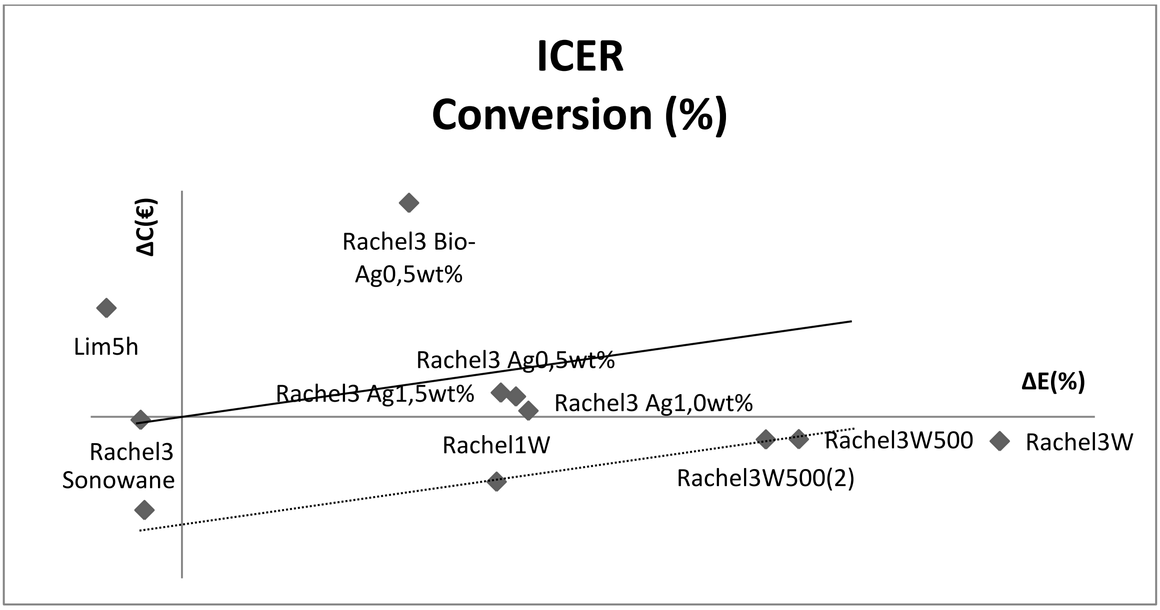

Figure VII.3. ICERs of synthetic photocatalysts of group 2 at 175 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in percentage

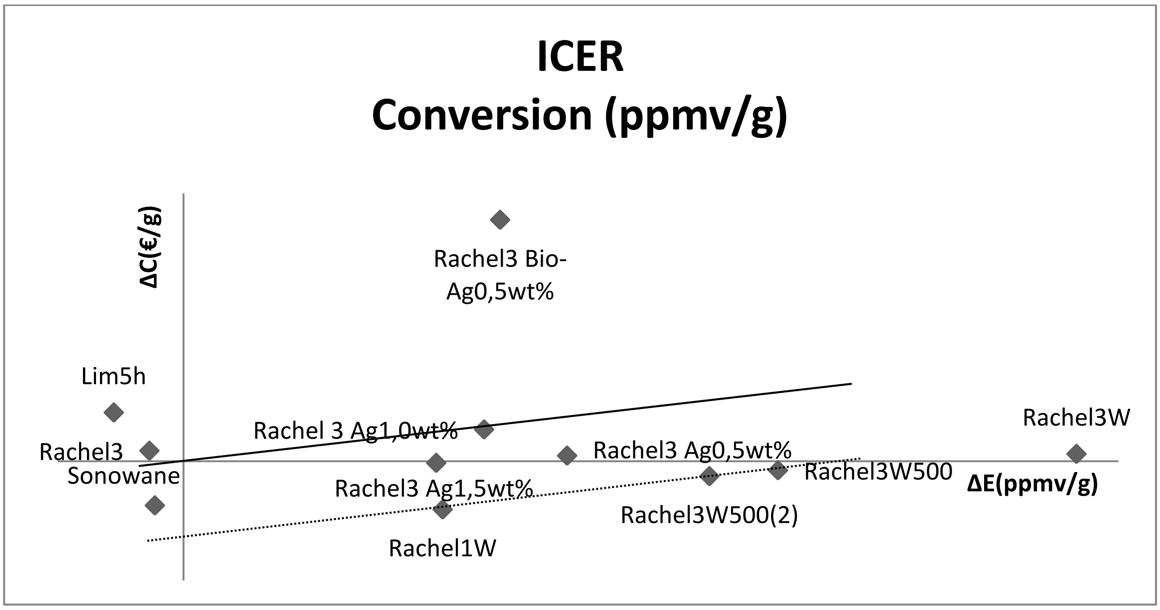

Figure VII.4. ICERs of synthetic photocatalysts of group 2 at 110 ppmv acetaldehyde intake and low kilowatt-hour cost with conversion in ppmv/g

Based on Figure VII.3 and VII.4, the exact same reasoning as with an acetaldehyde intake level of 110 ppmv applies. In this case, the threshold value with conversion expressed in percentage is 2.65×10^{-3}. Be sure to note that, in this case, when conversion is expressed in ppmv/g, only one threshold value is applicable, being 1.83×10^{-3}. If K is smaller than this value Rachel1W is to be advised. If K is larger, Rachel3W is more appealing. (Irrespective of the catalytic quantity used, Rachel1 and Rachel3W500 are equally appealing when K amounts to the threshold value.) Once again, because more importance is attached to the effectiveness of the materials, Rachel3W remains the optimal photocatalyst.

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Richting: **master in de toegepaste economische wetenschappen: handelsingenieur-technologie-, innovatie- en milieumanagement**
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Deckers, Nathalie

Datum: **30/05/2011**