TFTEI

TASK FORCE ON TECHNO ECONOMIC ISSUES

# VOC Abatement in the Packaging Printing Industry

TFTEI technical secretariat

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The methodology for estimation of costs of reduction techniques for VOC has been developed by the TFTEI Technical Secretariat. On this issue, developers are:

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To assist the TFTEI Technical Secretariat to develop the methodology for cost estimations for VOC, international experts have been involved.

The TFTEI Technical Secretariat is grateful to all experts for helping us.

At its 33th session in December 2014, the Executive Body (EB decision 2014/2 http://www.unece.org/index.php?id=33291#/) of the United Nations Economic Commission for Europe (UN-ECE) Convention on Long Range Transboundary Air Pollution approved the upgrade of the Expert Group on Techno-Economic Issues (EGTEI) to Task Force on Techno-Economic Issues, TFTEI. This report sometimes refers to existing EGTEI documents, but this designates TFTEI from now on.

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# 1 Introduction

The following report has been prepared in order to provide information on technical and economic parameters of NMVOC (Non-Methane Volatile Organic Compounds, in the following referred to as VOC) emission abatement techniques in the packaging printing industry. It is meant to update the existing documents that have been provided by EGTEI in 2003 (CITEPA 2003). Parts of this report are therefore a follow-up of the existing methodology; other aspects have been developed specifically in order to provide a detailed, yet easy to use approach to derive cost estimates for specific applications in an accuracy range of +/- 30%.

This report has been prepared in the context of the UNECE Convention on Long-range Transboundary Air Pollution. Therefore it is not focussing on specific regions or industries but providing a general overview of important aspects for the overall sector. We have developed a flexible methodology that can be applied to a broad variety of plants and applications in order to assess the economic and environmental effects of emission abatement measures.

Another purpose of this report is to provide data for the current revision of the BREF STS – the Reference Document on Best Available Techniques on Surface Treatment using organic Solvents. In accordance with the work that is currently conducted by the IPTS in Seville we focus on large installations with a solvent consumption of more than 200 t per year.

Industry information has been provided primarily by the industry associations ESIG (European Solvents Industry Group), FPE (Flexible Packaging Europe), FTA Europe (European Flexographic Industry Association) and Intergraf (The European Federation for Print and Digital Communication). We are very grateful to all the experts for their collaboration and provision of data and information.

# 2 Packaging printing industry overview

VOC abatement in large installations of the packaging printing sector, the relevant technological background and an approach for its economic evaluation will be presented in the following chapter. The information and the methodology provided are based on current research publications, industry information from plant operators and equipment suppliers as well as existing EGTEI/TFTEI knowledge. Regarding the technologies and typical plant configurations it was frequently mentioned by industry representatives that there is no such thing as a “typical site”. There is a broad variety of different combinations of processes that can be applied according to the needs of the specialization of the plant. Yet even regarding the existing areas of specialization there is no common ground, plants have specialized for example to one of these three categories:

- Specialization by material
- Specialization by product
- Specialization by market

Thus, we decided not to define reference installations and investigate them in further details, as the existing datasets for this approach are not sufficient and many installations would not fit into this approach due to one or several of the above mentioned issues. Yet we developed a general cost calculation methodology for the relevant primary and secondary measures that can be applied to a broad variety of plants. It is based on the current EGTEI methodology (CITEPA 2003), the US EPA methodology (US EPA 2002), scientific publications and on the industry information we received (also from other sectors if applicable). Within this report, we describe the specifics of the packaging printing sector and present the results of two exemplary case studies at the end. A more detailed description of the cost calculation methodology (ERICCa_VOC[1]) which is implemented in Microsoft Excel will be provided in two additional reports ("end-of-pipe technologies" and "technical document").

# 3 Considered technologies

We were informed by one important industry association regarding the type and share of technology that is used in the flexible packaging sector. It can be expected, that of all products in the sector, approximately:

- 80% are printed
- 50% are laminated
- 25% have a functional coating (i.e. not just a protective varnish)

Therefore, the existing and broadly applied manufacturing technologies for all three process categories are relevant and will be considered within this report. For printing, the two most common technologies are rotogravure with about 50% of the total production in Europe, regarding the members of the already mentioned industry association. The second most relevant technology is flexography with about 30% of the total production. Hence, these two technologies sum up to the above mentioned 80% of total production that is printed. Other technologies such as lithography or digital printing exist but are hardly used in this sector. Only for samples, very small batches or special materials they might be necessary and applicable. Therefore, they are not in scope of our work and will not be considered in the following. In general, rotogravure is faster and mostly suited for very large batches. Flexography is slightly more flexible and therefore better suited to medium to large batches and more frequent setting-up.

In general, the production of the Packaging Printing Industry is characterized by many start-ups, shutdowns and set-up interruptions due to the large number of products and variants. Both of the two most common printing techniques have different characteristics. Nevertheless the decision for one or the other technology is not only based on technical or economic aspects but also on historical developments (which technology is already installed in the plant and has maybe been used for a long time) as the quantity and quality of the output is comparable between the two technologies.

Apart from printing, there is coating, laminating and co-extrusion of films and coatings which are also important in terms of VOC abatement. The relevant technologies shall be presented in the following. Furthermore it is necessary to take the cleaning processes into account as well, as they often use solvents and can thus contain large VOC abatement potentials.

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[1] ERICCa_VOC: **E**mission **R**eduction **I**nvestment and **C**ost **Ca**lculation for **V**olatile **O**rganic **C**ompounds

## 3.1 Flexography

Flexography is a printing process using an image carrier of rubber or elastic photopolymers on which the printing areas are above the non-printing areas, using liquid inks that dry through the evaporation of organic solvents. The process is usually web fed and is applied for medium or long multicolour runs on a variety of substrates, including heavy paper, fibreboard, and metal and plastic foil. The major categories of the flexography market are flexible packaging and laminates, multiwall bags, milk cartons, gift wraps, folding cartons, corrugated paperboards (which is sheet fed), paper cups and plates, labels, tapes, and envelopes. Almost all milk cartons and multiwall bags and half of all flexible packaging are printed by this process. Water-based inks in flexography printing are in regular production use in some packaging applications such as paper and plastic carrier bags. Figure 1 shows a schematic illustration of the flexography process and the necessary components.

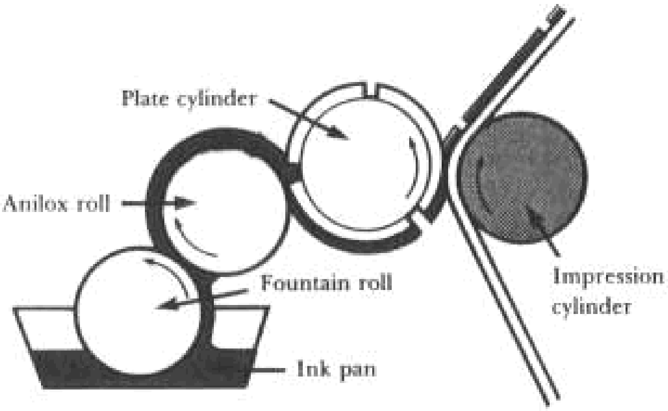

Figure 1: Schematic image of the flexography process (PNEAC 2015a)

Regarding the total share of Flexography in the Packaging printing sector, different statements exist. (CITEPA 2003) mentions a share of about 50% of all flexible packaging that is printed by this process. Another industry association refers to a share of about 30%. The deviation in this numbers might be caused by the fact that the definition of sectors varies greatly within this industry. Some differ by printing technology, others by product (like in this report) and still others by the material to be printed. It might also come from the number and region of countries covered by each study, as differences among countries and regions exist. Thus the overall numbers differ but there is certainly a large amount of flexible packaging that is printed using this process.

Water-based inks that contain very few or no solvents are the most important primary measures[2] in order to reduce VOC emissions in the printing processes. They have been used for flexographic printing of paper and paperboard since the invention of the process. Printing on these substrates with water was readily successful because of the absorbent nature of the paper fibres. The inks and solvents (water included) are partially absorbed by the substrate, and partially vaporized to the surrounding air. However, placing a waterborne solution on a film or foil

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[2] Primary measures are introduced in more detail in section 6.2 of this report.

is similar to placing water on a newly waxed car: the water beads up and slides over the surface. Surface tension differences between ink and substrate - particularly stressing the difference between solvent and water inks - requires modification of the substrate surface tension to facilitate the transfer and adhesion of the water inks. (Fachgruppe Druckfarben 2015; Shapiro 2011)

Figure 2 displays an overview of the necessary steps of the printing process, from preproduction to the finished product. These steps can be considered similar for both, water-based and solvent-based inks, yet the material and energy flows and the consumption of time and resources vary among different technical configurations.

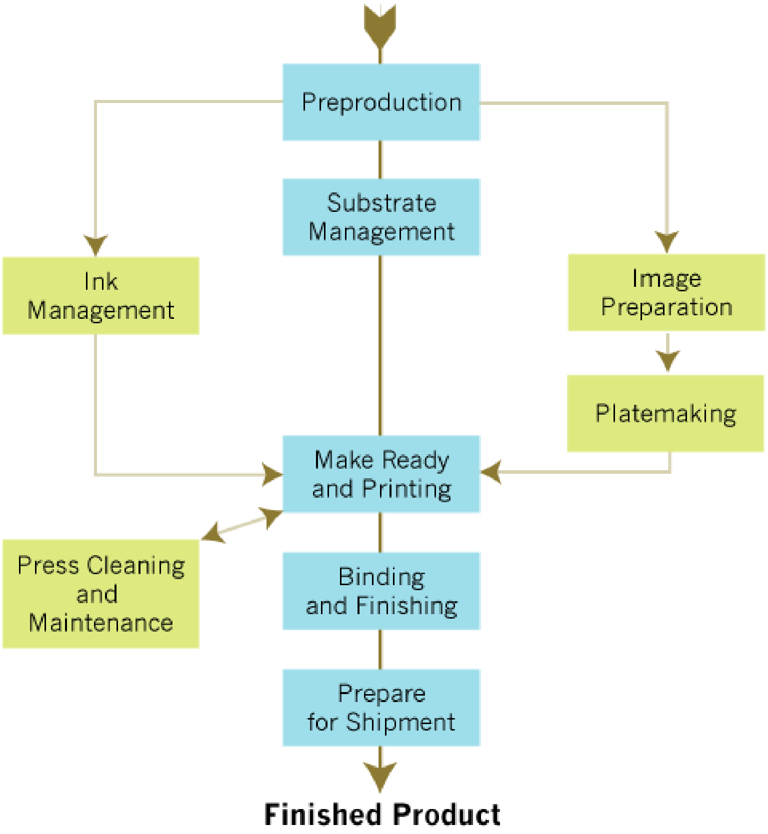

Figure 2: Flow-chart of the flexography process (PNEAC 2015a)

## 3.2 Rotogravure

Gravure printing is an example of intaglio printing. It uses a depressed or sunken surface for the image. The image areas consist of honey comb shaped cells or wells that are etched or engraved into a copper cylinder. The unetched areas of the cylinder represent the non-image or unprinted areas. The cylinder rotates in a bath of ink called the ink pan. As the cylinder turns, the excess ink is wiped off the cylinder by a flexible steel doctor blade. The ink remaining in the recessed cells forms the image by direct transfer to the substrate (paper or other material) as it passes between the plate cylinder and the impression cylinder (cf. Figure 3). (PNEAC 2015b)

The major unit operations in a gravure printing operation are:

- Image preparation
- Cylinder preparation
- Printing
- Finishing

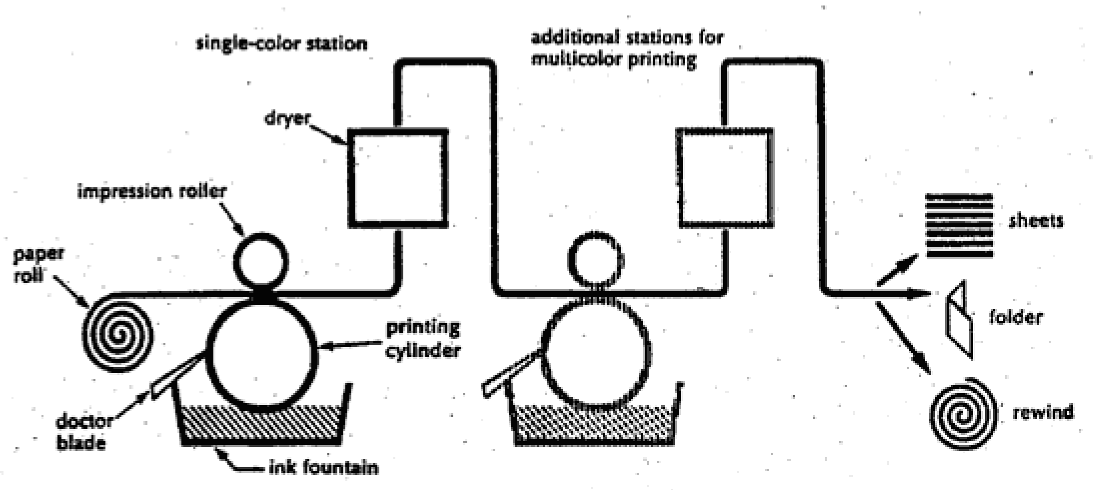

Figure 3: Schematic image of the rotogravure process (PNEAC 2015b)

Typical gravure printed products include:

- Food packaging
- Wall paper
- Wrapping paper
- Furniture laminates
- Panelling
- Greeting cards
- Magazines

Not all of these products belong to the packaging printing sector, yet the process is identical to the one used in the publication industry except for difference in size, speed and solvents used. (CITEPA 2003).

## 3.3 Coating

Coating is generally very closely related to printing, as it can in most cases be regarded as a very thick printing layer. It is usually done in-line with printing. Especially in the large plants we are considering within this report and there are four very common technologies:

- Direct Gravure
- Reverse Gravure
- Offset Gravure
- Smooth Roll

As the process is so similar to printing, we do not go into details as this would reach beyond the scope of this report. What has to be taken into account is the fact that basically all measures that will be discussed in terms of VOC abatement below can generally be applied to printing as well as to coating, even though there might be differences regarding the coating materials compared to inks in terms of solvent content, type of solvents and alternative products with lower solvent contents. (Ostness 2006)

## 3.4 Laminating

Lamination is the technique of manufacturing a material in multiple layers (at least two), so that the composite material achieves improved characteristics such as strength, stability, insulation, appearance or other properties. Possibilities to assemble the two (or more) materials are heat, pressure, welding, or adhesives. In the packaging industry, lamination is a very important process, as approximately 50% of all flexible packaging products are laminated. Products/processes that are mostly used for laminating are:

- Adhesives
- Wax
- (Co-extrusion of different materials)

The Co-Extrusion of different materials is an important technology that is applied a lot in the flexible packaging industry. Yet we are focusing on the packaging printing industry and thus on products that are printed first and laminated afterwards.

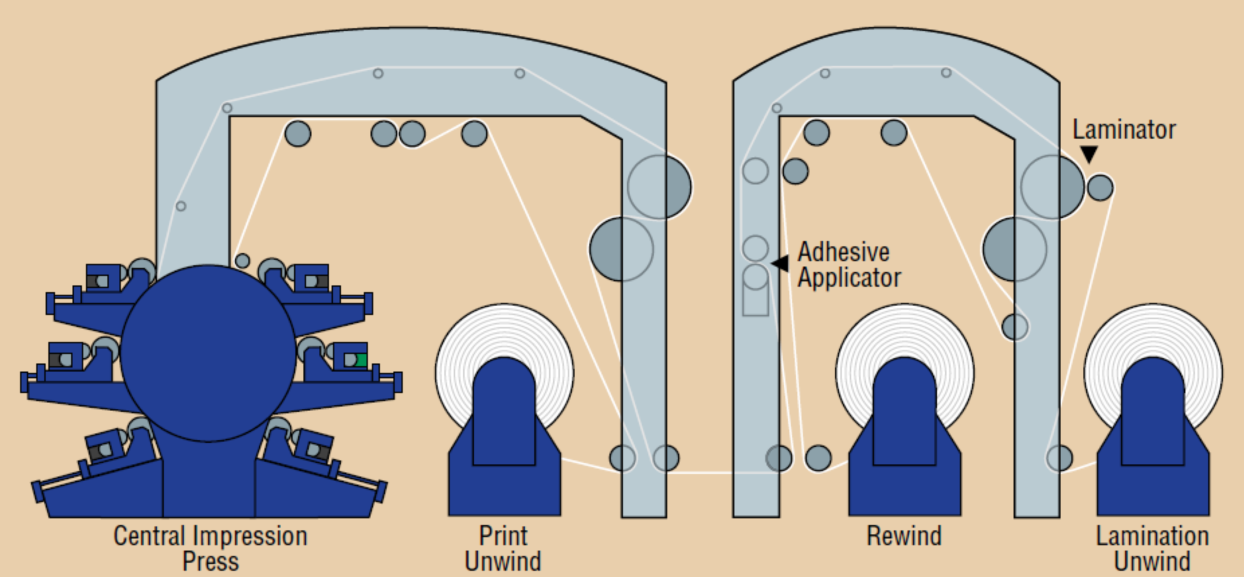

**Figure 4: Laminating setup with a separate and self-contained laminating machine in-line with a flexo press. (Voss 2002)**

Lamination can be installed in-line with printing (which is especially common in large installations) or separately. If it happens in-line and solvents are used it is very likely connected (or can be connected) to the same end-of-pipe VOC abatement technologies as the printing installation itself. The application of the adhesive takes place on one of the two surfaces which are pressed together continuously at speeds of 120 – 180 m/min. The drying process is done in the same equipment, using warm air at about 60 – 70 °C.

## 3.5 Cleaning

Cleaning is a very important and often underestimated process in the printing industry. Even though it is not producing or improving the production output itself, it has major influence on the quality and endurance of the machines. Furthermore, it often operates with solvents and thus provides several options for VOC abatement. There are two main cleaning processes: the automated cleaning of installations with the so called CIP (Cleaning in Place) technology and the manual cleaning of installations, products, containers, etc. with wipes and towels. Cleaning is very important in the printing industry in order to maintain the quality of the outputs. Even the slightest ink residues after changing the colour can lead to serious misprints. The solvent used depends largely on the equipment to be cleaned. For example, a blanket wash must dissolve ink quickly and dry rapidly with minimal wiping. Conversely, a solvent that is intended to clean a chain of ink rollers must evaporate slowly, to insure that it does not flash off before it has worked its way through all the rollers. (GEMÜ 2007)

Solvents have been and are still the most important cleaning agents in the packaging printing industry. Yet there are some new formulations of water-based cleaning agents which are especially useful for installations operating with water-based inks or varnishes. Cleaning of water-based inks can be done with water as long as the ink or varnish is not dry. There are even companies offering dry ice cleaning equipment in order to reduce the negative environmental impacts of the cleaning processes. More details about abating VOC emissions of the cleaning processes are discussed in chapter 6.

Cleaning is also an important source for fugitive VOC emissions, as cleaning wipes or towels are often taken out of the encapsulations of the machines and the evaporated solvents are thus no longer subject to end-of-pipe abatement techniques. Especially if wipes and towels are collected in open containers, they might emit significant amounts of VOC that do not only negatively affect the environment but also the personnel working inside the plant. (Pferdehirt 2005; US EPA Region 2 2014)

# 4 Inks and other products

Inks are the most important products for the packaging printing industry. However, as described above, there are other products such as varnishes, adhesives, cleaning agents, etc. that play an important role as well. In general, the type of product that is used depends very much on the final product, the quality needed, the technology in use and many other plant specific factors. The applicability of products is also limited due to chemical, physical or technical characteristics of the products and machines. It is thus not always possible to simply replace one product by a different one even though they might have comparable properties. Technical studies and tests are usually necessary in order to evaluate the applicability of a product in a specific context.

## 4.1 Types of Inks

There are four general types of inks often differentiated by the European Printing Ink Association (European Printing Ink Association 2015):

- Liquid inks water borne - this includes flexo and gravure water borne inks, technological varnishes, extenders, primers and overprint varnishes.
- Liquid inks solvent borne - this includes flexo and gravure solvent borne inks, publication gravure inks, technological varnishes, extenders, primers and overprint varnishes.
- Oil based inks - includes coldset and heatset offset as well as conventional sheetfed offset inks.
- All other inks.

As we are focusing on flexography and rotogravure, we only have to take liquid inks into account. Flexography and gravure inks are very similar and the constituents are essentially the same as they need to be fast drying and have a low viscosity. Oil-based inks are therefore not suitable for flexography and gravure. Other inks are for example UV- or EB[3]-curing inks. The amount of these very specific inks used in large installations of the packaging printing sector is, however, negligible so that they will not be considered in the following. Regarding the solvents in use for flexography and rotogravure, ethanol, ethylacetate and methoxy-/ethoxypropanol are the most common. (PNEAC 2015b, industry information)

In order to compare solvent-based and water-based inks in terms of alternatives for product replacement, there are a few differences that need to be considered. In order to maintain the quality of the final products, the two different inks must have the same effect on the substrate. Therefore, the solid content must be the same for both types of ink. A cost comparison between solvent based and water borne inks must therefore be based upon the amount of dry extract[4] (solid content). Other factors that need to be taken into account are the solvents needed for dilution, the energy required for the drying process and the disposal and treatment of waste. Water based inks typically require a higher temperature and longer drier exposure time. However, the lack of solvents makes it possible to recirculate the drying air more often and thus reduce the energy consumption. In practice, the increase in energy consumption for drying purposes may be about 10% according to the current BREF STS (Verspoor 2005; PNEAC 2015a; European Commission 2007).

## 4.2 Application and Sales Volumes

Figure 5 displays the sales volume of the European Printing Ink Association (EuPIA) members in 2015 in kilo tonnes. It shows that about half of the total amount of inks is generally suitable for the packaging printing industry (water-borne or solvent-borne inks). Water-borne inks are less than one third thereof, so that solvent based inks still seem to dominate the sector, even though we do not know which amount of these inks has been sold to the packaging printing industry. It is estimated, however, that the sample group accounts for about 90% of total industry sales in Europe. (European Printing Ink Association 2015)

In order to investigate the development of ink utilisation, a summary of the annual sales volumes between 2007 and 2015 is provided in Figure 6. It shows that the total consumption of inks reached a maximum in 2008 and 2010 but has been slightly declining since then. The volume of

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[3] UV: Ultra-Violet, EB: Electron Beam

[4] according to the nomenclature of the guidance document to the Gothenburg Protocol

solvent borne inks has declined even stronger while the volume of water borne inks has risen significantly. Yet the total amount of water borne inks is still a lot lower (less than half) of the total amount of solvent borne inks.

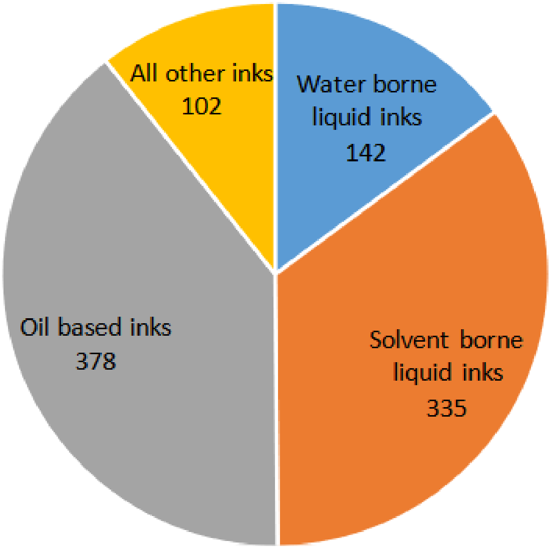

Figure 5: Sales volume of the European Printing Ink Association members in 2015 in [kt]. (European Printing Ink Association 2015)[5]

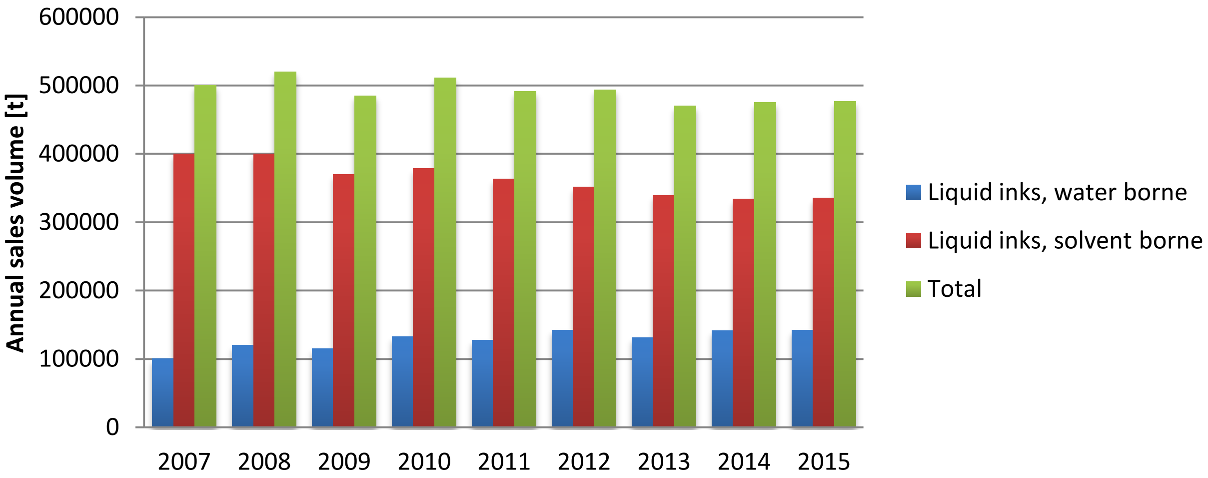

Figure 6: Annual sales volumes of water-borne and solvent-borne inks of the European Printing Ink Association members between 2007 and 2015.

The findings are based on the consolidated results of data supplied by EuPIA member companies. It is again estimated that the sample group accounts for about 90% of total industry sales in Europe and this stayed rather constant during the envisaged period (European Printing

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[5] The majority of these sales represent the EU countries as it is a European association. There are some non-EU or non-European countries considered as well, their volume, however, is negligible compared to the EU volume.

Ink Association 2007-2015). Yet it needs to be emphasised that we do not know the share of inks that was sold to the packaging printing industry. These figures also include other printing sectors, so that the precise results for the packaging printing industry might differ slightly. According to the qualitative information we received from industry associations, however, these figures display the situation of the packaging printing sector realistically (in terms of share and not in absolute numbers of course) so we expect them to be applicable for the packaging printing industry as well (cf. also Shapiro 2011).

According to the experience of the participants, the selection of inks is primarily depending on the technological feasibility, the available installations (company history) and on costs. Low-solvent or water-based inks are hardly applied primarily as a VOC emission reduction measure in the packaging printing sector; this is at most a positive side effect.

The composition of solvents (if solvent-based products are applied) can depend on two aspects. The most important is the type of substrates to be printed and the speed of the machines. But the waste solvent treatment may, if technically possible, influence the decision as well. In case of an existing solvent recovery installation, single-solvent is favoured whenever possible; in case of oxidation, mixed solvents are common, as they are often cheaper and/or more flexible. Hence, there is a strong interlinkage between technology and products that is interfering decisions in both directions so that the plant as a whole has to be regarded in terms of technology and product selection.

## 4.3 Other Products

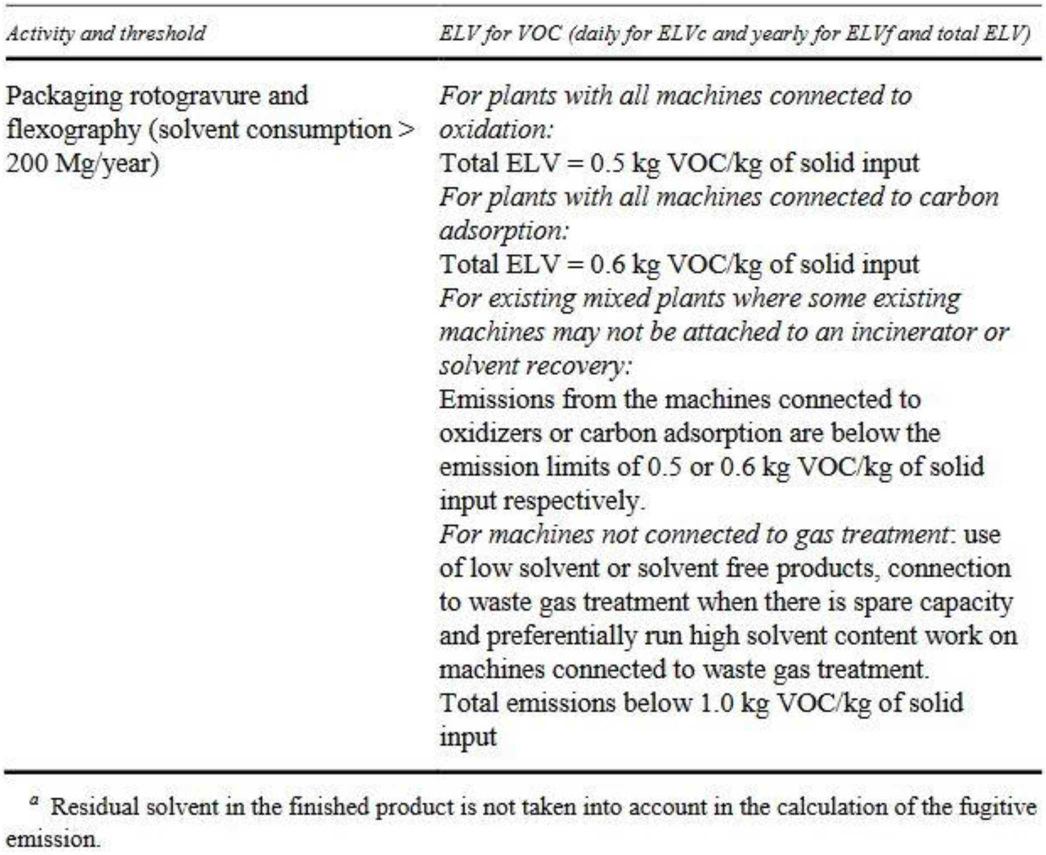
Other relevant products mentioned above are varnishes for coating and adhesives for laminating. For varnishes very similar developments to those described above for inks can be observed. There are more and more water based varnishes, but also for applications were water-based products are not suitable, there are low-solvent alternatives. According to (Deutsches Lackinstitut 2010) conventional varnishes have a solvent content of 40% to 50% by weight of the total product. High-solid products have a reduced solvent content of 22% to 30% and the newest generation of very-high-solids has an even further reduced solvent content between 12% and 20%.

Adhesives can consist of 100% solids, which is economically and environmentally favoured but not always technically feasible. They can also be solvent-based with different solvent contents (high-solid vs. low solid-adhesives) or water-based. Thus, there are applications were lamination can be done solvent free, but due to the characteristics of the substrate, the quality and properties of the final product or the technology in use, it might be necessary to use solvents in this process step as well, even though the properties of solventless adhesives have improved a lot over the last decades. Examples for water-based adhesives are polyurethane dispersions (which have in general very good properties but are often more expensive than solvent based alternatives) or acrylic polymer emulsions that are more suitable to less stringent applications in terms of product quality but very cost effective. Solvent based adhesives for plastic lamination are usually polyurethane-systems dissolved in ethyl acetate. The solvent content of the adhesive delivered by the producer is within the range of 30 - 50% and it is increased to 60 – 70% by adding solvent. (Voss 2002; European Commission 2009)

For cleaning applications a broad variety of cleaning agents can be used. Most of them are solvent based (especially if solvent based products are used in the machines), yet there are also water-based cleaning agents for water-based ink applications. Water based cleaning agents are causing lower VOC emissions, yet the treatment of the waste water within the plant can become more challenging, in order to avoid polluting the ground water. If solvent based cleaners are necessary, the cleaner should be selected carefully in order to minimize hazardous waste and air pollution. The material safety data sheets (MSDS) provide important information when considering purchasing a cleaner. Cleaning solutions with solvents or chemicals that would cause used cleaners to be classified as hazardous because of toxicity or flammability should be avoided. To reduce air pollution, cleaners with a low (no more than 30%) VOC content, a low vapour pressure (less than 10 mm mercury) and high flashpoint (above 60°C) should be used whenever possible. (Pferdehirt 2005; US EPA Region 2 2014)

# 5 Current European emission regulation

**Table 1: ELVs for large installations of the packaging printing sector according to the amended Gothenburg Protocol (UNECE 2013).**



| *Activity and threshold* | *ELV for VOC (daily for ELVc and yearly for ELVf and total ELV)* |
|---|---|
| Packaging rotogravure and flexography (solvent consumption > 200 Mg/year) | *For plants with all machines connected to oxidation:*<br>Total ELV = 0.5 kg VOC/kg of solid input<br>*For plants with all machines connected to carbon adsorption:*<br>Total ELV = 0.6 kg VOC/kg of solid input<br>*For existing mixed plants where some existing machines may not be attached to an incinerator or solvent recovery:*<br>Emissions from the machines connected to oxidizers or carbon adsorption are below the emission limits of 0.5 or 0.6 kg VOC/kg of solid input respectively.<br>*For machines not connected to gas treatment:* use of low solvent or solvent free products, connection to waste gas treatment when there is spare capacity and preferentially run high solvent content work on machines connected to waste gas treatment.<br>Total emissions below 1.0 kg VOC/kg of solid input |

[a] Residual solvent in the finished product is not taken into account in the calculation of the fugitive emission.

The current European emission regulation for VOC emissions is based on:

- The Gothenburg Protocol at the UNECE level, which sets emission reduction commitments for VOC and contains emission limit values (ELVs) as part of annex VI. Details about the regulation and implementation are provided in the guidance document of stationary sources (UNECE 2015b).

- The IED directive[6] (EU 2010) which includes the former directive 1999/13 of the reduction of solvent in industrial activities. According to this new directive, the permit conditions must ensure that ELVs set up enable to maintain the emission of the plant in the range of Best Available Techniques Associated Emission Levels (BAT AEL).
- The current BREF STS[7] (European Commission 2007). This document defines best available techniques that need to be applied in order to get a permission to operate a plant within the EU. This document is currently being revised by IPTS in Seville.

In the following, we provide a brief introduction to the current European legislation even though other regulations might apply for other parts of the world. Nevertheless the principles of worldwide regulating instruments are often very similar so that information about the European legislation and the specifics regarding the packaging printing sector might also be interesting for the rest of the world.

## 5.1 Emission Limit Values

The emission limit values (ELVs) for the packaging printing sector have been set-up in the Gothenburg Protocol of 1999. In its amendment in 2012, they have been revised completely. Now the ELVs for the packaging printing sector depend on the solvent consumption of the plant. As we focus on large installations with a solvent consumption larger than 200 t per year, the regulations displayed in Table 1 currently applies.

This protocol has not yet been ratified by a sufficient number of parties to be set in force. Furthermore there might be other national legislations in force with differing ELVs. Therefore the methodology described in the following is flexible to user inserted ELVs which are expected to often correspond with the ones mentioned above but are not obliged to do so.

## 5.2 Best Available Techniques

Besides the ELVs in the Annex of the Gothenburg Protocol and the related Guidance Document there are Best Available Techniques (BAT) defined in the current BREF STS (European Commission 2007). A plant specific selection of these techniques has to be applied in order to abate VOC emissions and thus to get a permission for plant operation. The BREF document is very detailed and shall thus not be discussed within the scope of this document. Important BAT categories for the packaging printing sector are substitution, recovery and destruction of solvents (with heat recovery). These categories are also considered in this report based on the most commonly applied abatement techniques. Yet this report serves as an information base for the current revision of the BREF STS, therefore we will not focus on the existing documents but provide a broad overview of current industrial and scientific information.

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[6] Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control)

[7] Reference Document on Best Available Techniques on Surface Treatment using organic Solvents

# 6 VOC abatement techniques

As mentioned above, there are four main types of solvents that are typically used in packaging printing industry and their emissions should be abated. These are:

- Ethyl acetate and higher esters,
- Ethanol and higher alcohols,
- Methyl ethyl ketone (for adhesives and coatings),
- Retarders, e.g. ethoxy propanol.

These solvents appear:

- In raw materials (inks, adhesives, coatings),
- As diluents to make inks etc. press ready and to maintain viscosity,
- As cleaning agents.

The selection and application of solvents does not only depend on their chemical and technical characteristics, but also on the existing installations within the plant. There is for example a difference between plants which recover solvents and those who do not. If solvents shall be recovered, a single solvent (usually ethyl acetate) is clearly favoured as it is technically very difficult to separate the different components of mixed solvents. Plants which do not reuse solvents tend to use solvent mixtures that have the most suitable chemical and technical characteristics and are economically favourable.

Regarding VOC abatement, there are two general types of measures that need to be considered. There are on the one hand primary measures directly reducing the amount of solvents used and therefore of VOCs released. On the other hand, there are secondary measures that reduce the content of VOCs in the exhaust gas. The most important secondary measures in this context are oxidation and solvent recovery, other measures exist but are hardly relevant for the considered sector.

Also measures exist which reduce the share of fugitive emissions of a plant. These measures are no real primary measures as they do not reduce the amount of VOCs released. Yet they neither directly reduce the amount of VOCs in the exhaust gas, thus they are no typical secondary measures. Therefore we will treat them as a separate category in the following. In the next sub-sections we will provide details about how to determine VOC emissions using the solvent management plan and the primary measures that are considered most relevant for large installations of the packaging printing sector. Furthermore we will give a short introduction to secondary measures, yet details will be provided in the separate “end-of-pipe technologies” report.

## 6.1 Solvent Management Plan

The solvent management plan (SMP) is a tool for the integrated assessment of solvent emissions of a plant. It is a standardised tool that can be applied for various sectors. Two input streams are balanced against nine possible output streams, yet not all of them need to be considered in every application. Figure 7 is providing an overview of all considered streams (UNECE 2015a).

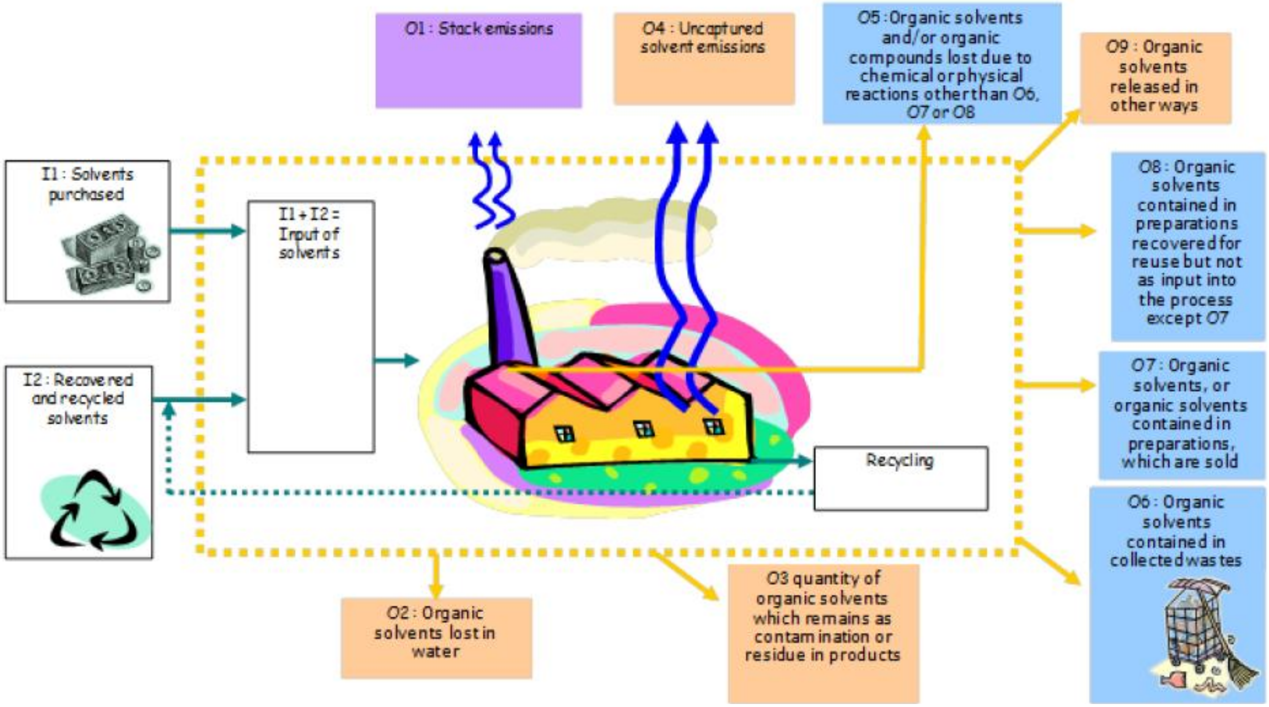

Figure 7: Illustrative example of a solvent management plan (UNECE 2015a)

The most important input is I1, I2 only needs to be considered if some sort of solvent recovery is implemented.

Regarding the outputs, O1, O4, O5 and O6 are of general importance.

O7 might become relevant in some activities such as ink and paint production where solvent-based products are sold externally. For the packaging printing sector, however, O7 is usually not present. O8 might become important in some plants if solvents are recovered.

O2, O3 (solvent in ink residues on substrates) and O9 are (or should be) hardly important for the regarded sector.

The solvent management plan is necessary to assess the achievement of ELVs, especially if not the total emissions, but the combination of fugitive and stack emissions is regarded (as described in chapter 5.1.

More information about the SMP, its structure and examples for its correct use is provided in (UNECE 2015a).

## 6.2 Primary Measures

The most relevant primary measures applied in this sector are all based on one common principle. High solvent content products should be replaced by products with lower solvent contents. Therefore, various alternatives exist:

- Solvent-based products with lower solvent contents

- Water-based products
- 100% solid products (for lamination)
- UV curing or other special inks

Of course not all these measures are suitable for all types of processes. Depending on the required quality of the output, the existing installations, etc. some alternatives might be technically limited or economically unfavourable. More details about limitations and cost effects are discussed in sections 6.5 and 7.1

Another theoretically feasible primary measure is the reduction of solvent consumption by reducing the necessary amount of products. As for the final output this measure would massively influence the quality, it is not considered in the following for the direct production processes (printing, laminating and coating). The amount of cleaning agent, however, can be reduced in many cases and thus this measure can be applied as well in this context. In the following, we will provide an overview of measures in order to reduce VOC emissions from cleaning processes:

1. Reduce the need for cleaning:
   - Improve production methods by coordinating runs according to colour, type or quantity, thereby reducing the number of clean-ups.
   - Use standard sequence on process colours to minimize colour changes for presses.
   - Run similar jobs simultaneously to reduce cleaning.
   - Clean ink fountains only when changing colour; use spray-skin overnight.
2. Use alternative solvents:
   - Review the types of inks used and the solvents needed to clean presses after their use.
3. Reduce solvent use in cleaning:
   - When solvents are essential for cleaning, alternative cleaning methods can reduce the amounts of solvents used:
     - Avoid soaking cleaning wipes in solvent. Use pump or squeeze bottles to dampen wipes.
     - Utilize parts washing equipment as an alternative to towels for cleaning the trays that collect the solvents and inks below each press roller.
     - A parts washing unit with recirculating solvent can be used. Trays can be removed from the press and placed in the washer unit where solvent is used in a closed washing system to remove the ink.
     - Lightly used shop rags can be used for non-critical cleaning.
     - Scrape excess ink from surfaces before wiping down.
   - Remove excess solvent from wipes:
     - Excess solvent can be removed from used wipes by hand wringing, mechanical wringing, or spinning in centrifuge.
4. Collect solvent waste for recycling:
   - Use efficient methods of collecting solvent waste while reducing the chance of spills.
   - Provide clearly marked drums or containers to collect solvent waste.
   - Modify drain trays as necessary to make it easy and neat to pour or drain collected solvents into storage drums.

- Add receiving funnels with automatically closing covers to storage containers to decrease spills and air pollution from evaporation (cf. chapter 6.3)

(Pferdehirt 2005; US EPA Region 2 2014)

Regarding very recent technologies, dry ice cleaning is meant to be very environmentally friendly. The idea is to treat surfaces with dry ice consisting of $CO_2$ that breaks up the ink or other product layers and evaporates afterwards, so that a residue-free cleaning is possible. We were not able to gather any cost data or experience reports regarding this new technology yet it should be considered when discussing alternatives to reduce cleaning emissions.

## 6.3 Fugitive Emission Reduction

*Fugitive emissions "enter in the atmosphere without passing through a stack or duct designed to direct or control the emissions. They include uncaptured emissions released to the outside environment via windows, doors, vents and similar openings."* (UNECE 2015b)

(Verspoor 2003) provides a whole list of possible sources of fugitive emissions for the flexible packaging sector. Even though this reference is not the most recent we consider many of these issues still relevant depending on the condition of the equipment installed in a plant.

- Press room ventilation during printing
- Dryer ventilation during make ready
- Dryer ventilation while waiting during stops
- Local exhaust between press units
- Cleaning department
- Ink mixing department
- Solvent content of water based inks, varnishes and adhesives
- Solvents used on machines not connected to the incinerator
- Residual solvent in products
- Solvents discharged in water
- Solvent emissions from waste water treatment
- Vapour losses from tanks, etc.

In order to reduce fugitive emissions, the most valuable tool is the solvent management plan as it displays a possible need for reduction. Reducing leakages and ventilation systems deficits are then the first steps. Furthermore (US EPA Region 2 2014) recommends explicit measures (e.g. keeping used shop towels in closed containers, etc.) to reduce evaporation of solvents. If all this is not sufficient to meet the abatement goals, a total pressroom capture is recommended in order to collect all the exhaust gases within the pressroom. Yet this might of course be difficult due to the building substance of the factory and needs to be designed carefully according to the specific circumstances.

The (European Commission 2009) also recommends specific measures to reduce fugitive and process emissions of the lamination process that can, however, be applied to many printing and coating processes as well:

- Enclosure of the lamination equipment and thermal oxidation of the exhausted air.

- Efficient ventilation around the lamination equipment in addition to the ventilation system of the equipment itself. Automatic doors and closed windows reduce fugitive emissions effectively.
- Enclosed in-line equipment for adding solvents to the adhesives for adjustment of solid content and viscosity before application (prevention of solvent losses to air).
- Good housekeeping for adhesives, solvents and solvent-containing waste. These are mostly simple measures like preventing open cans or drums containing solvents, solvent containing products or waste like residues and cleaning rags.
- Installation of solvent-storage tanks with vapour return pipes.

## 6.4 Secondary Measures

The most important secondary measures for the packaging printing sector are thermal oxidation and activated carbon adsorption with solvent recovery. Other secondary measures such as biodegradation are according to industry information hardly ever applied and technically limited for the application in the packaging printing sector. They shall therefore not be in the scope of this work.

For oxidation three general technologies exist: regenerative, recuperative and catalytic oxidisers. Regenerative oxidisers are by far the most common in the packaging printing industry, even though the others are technically feasible as well. Solvent recovery is mostly used in Italy whereas it is not very common in the rest of Europe due to its technical limitations, as it is mostly suitable for single solvent applications.

Due to the large amounts of solvents that are handled in the big installations of the packaging printing sector and the good exhaust gas management through encapsulations etc., the sector can be considered as a typical application for secondary VOC abatement measures where no general difficulties apply. Preconcentration units are usually not necessary in this sector, unless the VOC content of the products is reduced very much (for example by applying low solvent or water-based products).

A detailed description and economic evaluation of the relevant secondary or so called end-of-pipe technologies is provided in the separate “end-of-pipe technologies” document.

## 6.5 Limitations for VOC Abatement

There are many reasons and possibilities to reduce VOC emissions and thus to protect the environment and human health. Yet, there are as well some negative outcomes and cross-media-effects or technological difficulties that limit the dissemination of specific VOC abatement measures apart from solely economic aspects, such as higher capital or operating expenses. These effects are often very plant specific and need to be analysed in detail based on the applying circumstances. Some general issues apply frequently and will thus be presented in the following subchapters in order to provide a broad overview.

### *6.5.1 Cross-Media-Effects*

As the technological dependencies between processes, products and output are very strong in the packaging printing sector, various cross-media-effects need to be taken into account when switching to a new technology or product. Some of them are occasional, such as the higher risk of ground water pollution when applying water-based inks, others are technology inherent, such as $NO_X$ emissions from thermal oxidisers. The (European Printing Ink Association 2013) is summarising these interdependencies in a very descriptive manner:

“For example, the term “water based” suggests something environmentally friendly and likewise, “vegetable oil based systems” may be considered favourable because of their renewable source content. In some instances, however, these products may in fact need significantly more energy to dry than alternative materials and studying the ‘big picture’ may reveal that they have less beneficial environmental impact than first thought. Furthermore, the type of substrate may also influence the overall impact: significantly more energy is needed to dry water based inks on plastic or metal substrates, than on a substrate such as corrugated paper. In reality, no single ink technology or printing process will provide a universal environmental solution. The determination of the most appropriate option can only be identified by all parties involved in the particular process or product, taking the relevant factors into account.”

The most important cross-media-effect that has already been mentioned in the citation is rising energy consumption for basically all emission reduction measures. Regarding primary measures, for example especially water-based inks need more energy for drying. For secondary measures, additional energy is necessary for fans and capturing devices in order to overcome the additional pressure drop caused by the installations. In the case of oxidation, additional energy (usually natural gas) might be necessary if the VOC concentration in the exhaust gas is not sufficient to maintain the combustion process at auto thermal conditions. Apart from the additional drying energy for primary measures, which is quantified to approximately 10% by (European Commission 2007) but can hardly be determined quantitatively for a broad variety of installations, these effects are considered in the calculation methodology of ERICCa_VOC in terms of costs, but not in terms of total emissions of the plant (as we are focusing on VOC emissions only and a lot more data would be necessary to assess the overall emissions of a plant).

An exemption thereof is the greenhouse gas emission of thermal oxidisers. Depending on their mode of operation (below or above the auto thermal point, for details cf. “end-of-pipe technologies”-document), they emit direct greenhouse gases $CO_2$, $CH_4$, $N_2O$ and other pollutants such as NOx  and CO. Indirect $CO_2$ emissions from electricity consumption are also provided.

The amount of these substances emitted is calculated in ERICCa_VOC in order to provide this information to plant operators.

Other cross-media-effects might exist but are, as already mentioned, very plant and application specific and shall therefore neither be considered in ERICCa_VOC nor will they be in scope of this report.

### *6.5.2 Technological Difficulties*

The technological difficulties can be separated by technology or by product. Some issues only occur when using specific technologies; others are mainly relevant for product variation, such as switching to alternative inks. In the following we will first describe the **Lower Explosion Limit**

**(LEL)**. Afterwards, some important issues regarding the switching from solvent-based to water-based products will be discussed.

The LEL is one important parameter that needs to be kept in mind when designing an exhaust gas treatment system. In general, in order to minimize energy consumption exhaust gas flow rates shall be kept low. This, however, is only possible to a certain extent, as the solvent content of the airflow should not exceed 20 - 25% of the LEL (European Commission 2009). LEL for organic compounds are listed in chemical parameter databases. According to (US EPA 2002) a reference value for the LEL of most solvent-air-mixtures is around 1860 kJ/Nm³. Using the lower heating value (LHV) of the applied solvent, the acceptable solvent concentration can be calculated. For an LHV of 30 kJ/kg the LEL concentration is about 62 g/Nm³, so that 25% thereof would be approximately 15 g/Nm³ as maximum permitted solvent concentration in the exhaust gas. It needs to be emphasised that this calculation is rather basic and does not include all the technical and physical details. Nevertheless, it provides a good estimation in order to get an order of magnitude value.

Regarding possible technical difficulties when switching from solvent-based to low-solvent or water-based products, (Shapiro 2011) is providing a broad overview. Some important examples will be provided in the following, more details can be found in the original publication.

<u>Ink transfer system:</u>

- The ink transfer system requires attention to ensure the metering capabilities of the components and the structural nature of the rollers. (Other texture of the ink, corrosion, etc.)
- It is important that the metering rollers are in continuous motion when water-based inks are in the printing station. Re-wetting of all surfaces is critical as dried water-based ink is like cement. This is most important during press stoppages. Older press configurations and in-line units do not always have this feature and must be modified.

<u>Drying system:</u>

- Drying systems that were more than adequate with hydrocarbon solvents can be totally inadequate for water. (Solvents typically evaporate quickly)
- The volume of the vapours from water-based products is up to 10 times the volume of solvent-based given the same liquid volume as a starting point.
- Drying systems have to be rebuilt or equipped with better air movement and much higher exhaust gas rates.
- The drying speed is also important. Production on a high-speed press will be limited if the air flow is inadequate. A general finding with water-based inks on existing high-speed presses is a loss of 25% to 30% of the production speed when running it with drying systems designed for solvent-based inks.

<u>Pre-Treatment:</u>

- Film surfaces must be pre-treated in order to raise the surface tension for printing. Pre-treating units (corona or flame) are required to make the surface of the film more receptive to the water-based inks.

Auxiliary Systems:

- Ink pumps that were used with solvent-based products are often not compatible with water-based ones. The fast impeller speed promotes foaming of the water-based inks. New pumps might have to be obtained.
- Printing plates may have to be changed to different base materials with surface tensions that will accept and transfer inks more adequately.

Solvent recovery equipment:

- Solvent recovery equipment is not suitable for the recovery of water-based inks. New technology (i.e. evaporation or ultrafiltration), or the off-site removal of this waste, may be required.

Management:

- Personnel must be trained to utilise new methods in the setting up and cleaning of presses to ensure that inks do not dry on the rollers, on plates, or other parts of the machinery.
- A major effort has to be made in the methods used in setting up, operating and breaking down presses. The transfer characteristics of waterborne inks are such that the work force has to be completely trained in the use and troubleshooting of the new inks. Solvent-based inks were very forgiving; water-based inks are not.

Regarding **lamination**, the (European Commission 2009) is providing some more technology specific limitations when switching from solvent to water-based adhesives:

Sterilization: The adhesives cannot handle high temperatures for a long time

Chemical resistance: Diffusion of certain chemicals (acids, alkaline, certain flavours) can cause serious damages to water based adhesives

Adhesion properties: They can be especially critical if acrylic emulsions are used

Cost and Consumption: Water based adhesives are usually cheaper than solvent based ones and contain less than 2% VOC. The energy consumption is higher due to the thermo-dynamical properties of water compared to solvents (enthalpy of evaporation for water is more than twice that of solvents).

# 7 Cost Calculation

The cost calculation for the packaging printing industry as described below has been fully implemented in the ERICCa_VOC tool. A full description of this tool with all calculations and equations can be found in the technical document. In order to facilitate the reading and understanding of this document and the general methodology, equations will not be mentioned in this chapter (unless they are necessary for exactly these purposes).

## 7.1 Primary Measures

The cost calculation for primary measures in the packaging printing sector will be presented in the following. The results of these calculations are part of the final cost summary on the one hand and on the other hand, the emission reduction achieved by these measures serves as input for the calculation of secondary measures. The reduction of fugitive emissions is part of this subchapter as well and will also be addressed in the following, as this will influence the amount and concentration of the exhaust gas to be treated by secondary measures.

### *7.1.1 Investment*

We would like to enable the users of ERICCa_VOC to consider investments for primary measures. These may be necessary as a substitution of products might cause a need to modify the existing printing installations in order to ensure the quality of the output for example. Yet the situation is very specific in individual plants so that we cannot provide an average reference value which is valid for a broad variety of plants. It depends on the products and the process equipment installed. The investment accounts for:

- Research and development, product testing and permissions
- Adaptations of the process equipment (dryers, cylinders…)
- Water treatment process

An average investment of 25.000 - 190.000 € per varnish or adhesive has been mentioned in the existing EGTEI study (CITEPA 2003). It is recommended to use 75.000 € per substituted product or 1.500 € per ton of ready to use product in this document. These numbers only account for the above mentioned investment components but not for higher prices of new products. It is confirmed by (Voss 2002) that the derivation of investment data in a general manner is very difficult. He gives the example of lamination: for some water-based adhesives a capital expenditure is necessary to update the meter-mix-dispensing unit with heating capabilities. Other adhesives, however, can be pumped and mixed at room temperature through existing meter-mix dispensing units. As we are lacking better/more data, we decided to keep the examples from the existing documents in terms of reference values, yet we encourage every user of the methodology to carefully check the necessary investments necessary for product replacements.

In terms of cleaning, the measures are not only important in terms of VOC abatement; they might also result in cost savings due to lower consumption of cleaning agents. On the other hand there might be capital expenses for equipment such as centrifuges or washing equipment, yet in comparison to the installations and consumptions of the overall plants these expenses as well as cost savings are expected to be of rather low influence and are thus not considered in the tool.

The fugitive emission reduction that was explained in chapter 6.3 may also cause additional investment. Even though it is not a typical primary measure, we consider it within this subchapter as it influences the amount of VOCs that have to be treated by secondary measures. Yet it is again a difficult task to name a reference value for a broad variety of applications. Many of the already mentioned measures are more of an organizational type (such as closing lids of product containers, storing cleaning wipes in closed containers, etc.) and hardly require any investment. Others – such as encapsulation of installations or a total pressroom capture – might cause massive investments and need to be regarded in terms of investment calculation. Therefore we implemented an input variable accounting for investments of this kind, yet the reference value is 0 so that the user can input its specific data if it is available or can be estimated.

### 7.1.2 Operating Costs

The considered operating costs of primary measures consist of deviations between the prices of conventional and replacing products. Low-solvent products might be more expensive and thus generate higher costs in case of a substitution. If, on the other hand, the price of the substituting product is lower, which is, according to (European Commission 2009) often the case for water-based adhesives, but also for other water-based products, the application of primary measures might gain savings that will be considered by ERICCa_VOC. The cost for additional energy consumption due to worse drying properties, or in case of solvent based inks and the cost for additional solvents needed for dilution also have to be taken into account in order to compare the total operating costs. (Shapiro 2011; European Commission 2007)

## 7.2 Secondary Measures - Oxidation

The description of the cost calculation for the secondary measures (oxidation and adsorption) will be kept very short in this document, as these calculations are described in detail in the “end-of-pipe technologies” document and the “technical document” of ERICCA_VOC. Therefore just a very broad description will be provided in the following.

### 7.2.1 Investment

In order to calculate the investment for oxidisers (pollution control equipment expenditure), a cost curve has been developed based on data from recent industry applications. The resulting equation in order to determine the cost for oxidisers depending on the flow rate (FR) in [Nm³/h] of the installation is:

$$\text{Investment}\ [€_{2014}] = -1{,}5 * 10^{-5} * \text{FR}^2 + 7{,}875 * \text{FR} + 212.233$$

This curve is valid for regenerative as well as recuperative oxidisers and also for large installations with preconcentration wheels (which are, however, not very common in the packaging printing sector).[8] The validity of the equation is limited to a maximum flow rate of 220.000 Nm³/h

It needs to be emphasized, however, that the operating costs of regenerative and recuperative oxidisers can differ a lot due to their different technical setup. This will be further discussed in the following section.

A factor for installation expenditure is added to the value resulting of the investment equation that accounts primarily for the integration of the equipment into the plant. A reference value of 1,85 has been determined from existing applications, yet it can be adapted if more detailed data about the complexity of the installation is available.

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[8] This issue was explicitly confirmed by an equipment manufacturer

### *7.2.2 Operating Costs*

The operating costs of oxidisers can be divided in variable and fixed operation costs and benefits that may be gained from using excess heat in external processes within the plant. Regarding the consumption parameters, not only the state of operation (below or above the auto-thermal point (ATP)) but also the type of oxidiser used is important.

Regenerative oxidisers reach the auto-thermal point usually more easily and might therefore have lower natural gas costs. This is expected to be one of the main reasons why this technology is the most common in the packaging printing sector.

In the following, the most important cost components are listed. As mentioned before, more details can be found in the related documents.

Variable operating costs:

- Electricity
- Natural gas (below ATP)
- Cost of labour (maintenance)

Fixed operating costs:

- Maintenance cost (without labour)
- Insurance and taxes

Benefits:

- Heat recovery for external processes

## 7.3 Secondary Measures - Adsorption and Solvent Recovery

For adsorption and solvent recovery, it has not been possible yet to gather enough data in order to set up an investment curve comparable to the one for oxidation, as there are far less installations existing in Europe. Therefore the US EPA methodology has been used in order to calculate the investment for this type of installations. The operating costs are calculated in a similar manner compared to oxidation, taking the process characteristics and in- and outputs of adsorption into account.

### *7.3.1 Investment*

As described above, this approach is based on the methodology described in (US EPA 2002). Yet we made some simplifications as the original methodology is very detailed. A study-level estimation without to many necessary input values can be achieved with this simplified methodology, too.

Adsorber geometry:

The first step is to calculate the adsorber geometry. Therefore the following input values are necessary:

- Number of desorption and adsorption units
- Adsorption time

- Maximum Flow Rate

Thereof, the desorption time, the required amount of activated carbon and the length, diameter and finally the surface of the adsorber unit is calculated. The diameter per unit should not exceed 4 meters; the maximum length is 15 meters. If the calculated values exceed these thresholds, additional units should be added.

Investment function:

Based on the surface of the adsorber unit, the investment per unit is calculated using the following equation:

$$\text{Invest}_{\text{unit}}[€]= \left(271\left[\frac{€}{\text{m}^2}\right] * \left(\frac{\text{Surface}}{0{,}0929}[\text{m}^2]\right)^{0{,}778} * 1{,}1097\right)$$

The factors 0,0929 and 1,1097 are inserted in order to convert feet in SI units (meter) and $-1999 in €-2014[9]. The resulting investment can be corrected for different materials, by applying a material factor (i.e. for stainless steel or titanium). The cost of the initial filling of activated carbon is added to this value before applying a scale factor for the maximum flowrate in order to account for economies of scale. Finally a factor for auxiliary installations is applied to consider the integration of the system into the overall plant.

As mentioned already, detailed technology descriptions, more information about the calculations and the equations as well as reference values are provided in the "end-of-pipe technologies" and the "technical document" of ERICCa_VOC.

### *7.3.2 Operating Costs*

The structure of the operating cost calculation for adsorption installations is very similar to the one that has been described in 7.2.2 for oxidation. Some components are identical, others have to be replaced or inserted (such as the carbon cost or the cost for vapour/nitrogen).

Variable operating costs:

- Electricity cost
- Carbon cost
- Cost of vapour/nitrogen
- Cost of labour (maintenance)

Fixed operating costs:

- Maintenance cost (without labour)
- Insurance and taxes

Benefits:

- Benefits from recovered solvents (either reused internally or sold externally)

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[9] The factor has been derived from historical currency exchange values and includes the development of the CEPCI-index as well.

In order to keep this description simple, we will not go more into details, as they are provided in the related documents.

## 7.4 Exemplary Calculation Results

The following calculation examples represent “typical” installations of the packaging printing sector, even though the wording “typical” is regarded very critically by industry representatives, as every plant in the packaging printing sector is individual. Nevertheless, we think, these plants could exist and provide some examples about VOC abatement and the related costs for the sector. Again it shall be emphasised that these are only examples – under different circumstances the calculation might differ, yet this is the reason why we implemented such a flexible tool as ERICCa_VOC that can easily be adapted to the specific needs of various users. Again we do not provide all the calculations and background data in order to keep this document readable. Yet the calculation can be reproduced based on this data (and some reference values provided in the tool) in order to analyse it in more detail and the equations can be checked with the technical document.

The reference plant is a medium sized plant for flexography printing (150 t of solvent based inks per year) and lamination (20 t of solvent based adhesives per year). Together with additional solvents for dilution and cleaning, the total solvent input is 332 t per year. The VOC emissions (stack emissions and fugitive emissions) without any measures are 327 t/a. After the installation of primary measures and a recuperative oxidation they are reduced to 24,6 t/a, i.e. 0,31 kg VOC emissions/kg of solid input which is below the emission limit value of 0,5 kg VOC emissions/kg of solid input.

### *7.4.1 Primary Measures*

There are no changes made to the flexography process. However, the lamination process is changed into a solvent free process by application of a 100% solid adhesive. Besides, no changes in solvent management (reduction of fugitive emissions) are envisaged. The plant shall be equipped with a recuperative oxidiser, which is operated above the auto thermal point. A pre-concentration of the exhaust gas is not considered but the recuperation of process heat from the stack gas shall be considered.[10]

In the following, the calculation of the emission reduction measures in terms of costs and emissions abatement is provided step by step. The blue cells in the screenshots are input fields that need to be filled in by the user. The green cells are providing results that are executed automatically by the tool.

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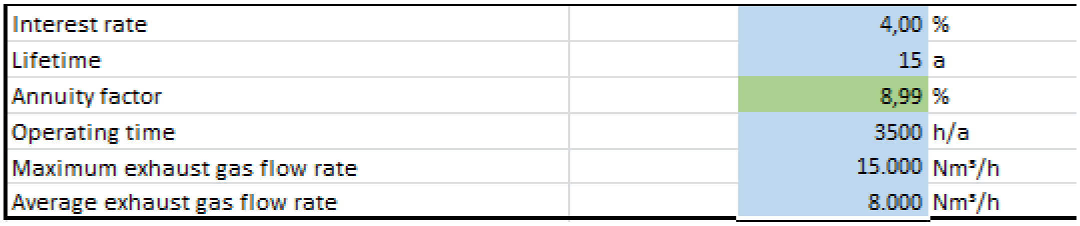
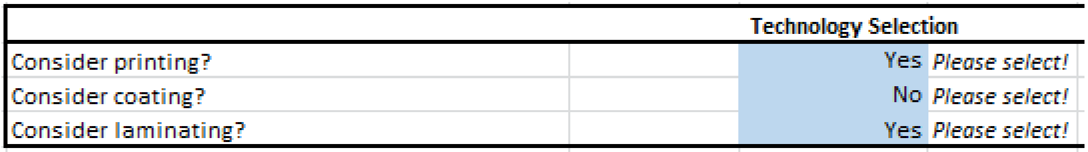
[10] In order to consider process heat generation from oxidation it needs to be checked first, if there is a possibility to use the heat in the plant or the surrounding area (i.e. district heating system). If this is not the case, the heat could be recovered but will not generate any revenues or savings and should thus not be considered in the calculation.



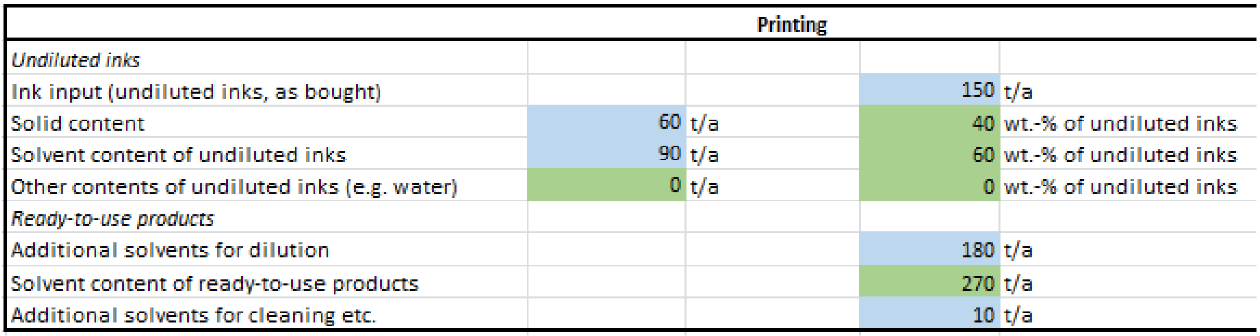
| | | | |
|---|---|---|---|
| Interest rate | | 4,00 | % |
| Lifetime | | 15 | a |
| Annuity factor | | 8,99 | % |
| Operating time | | 3500 | h/a |
| Maximum exhaust gas flow rate | | 15.000 | Nm³/h |
| Average exhaust gas flow rate | | 8.000 | Nm³/h |

The first inputs are the overall plant characteristics that will be important later on for the calculation of annual costs and VOC concentration and emission values. Thereafter, the technologies to be considered need to be selected. In our case, as mentioned already, it is printing and laminating.

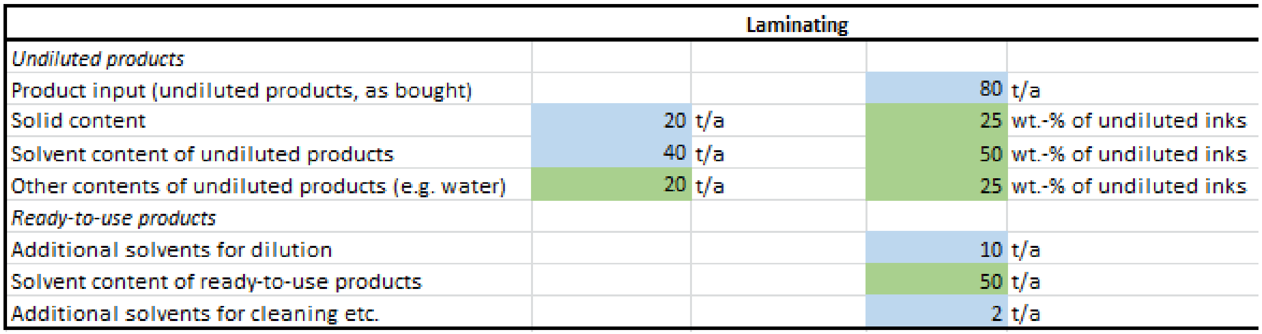


| | | Technology Selection | |
|---|---|---|---|
| Consider printing? | | Yes | *Please select!* |
| Consider coating? | | No | *Please select!* |
| Consider laminating? | | Yes | *Please select!* |

Afterwards, the consumption data of the considered processes before product replacement have to be provided:

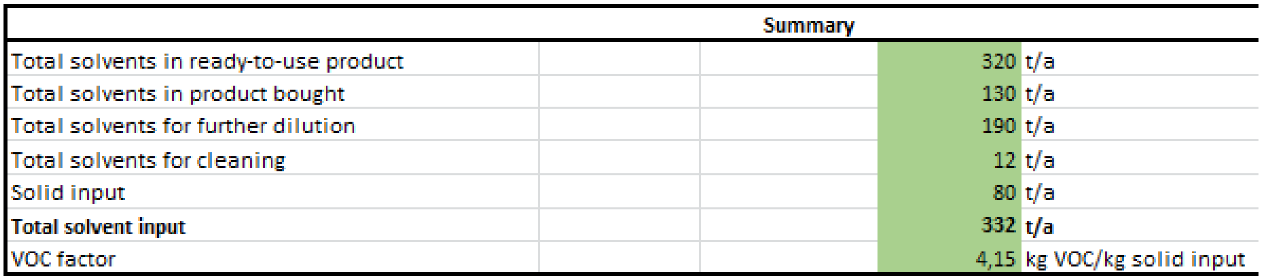


| | | Printing | | |
|---|---|---|---|---|
| *Undiluted inks* | | | | |
| Ink input (undiluted inks, as bought) | | | 150 | t/a |
| Solid content | 60 | t/a | 40 | wt.-% of undiluted inks |
| Solvent content of undiluted inks | 90 | t/a | 60 | wt.-% of undiluted inks |
| Other contents of undiluted inks (e.g. water) | 0 | t/a | 0 | wt.-% of undiluted inks |
| *Ready-to-use products* | | | | |
| Additional solvents for dilution | | | 180 | t/a |
| Solvent content of ready-to-use products | | | 270 | t/a |
| Additional solvents for cleaning etc. | | | 10 | t/a |



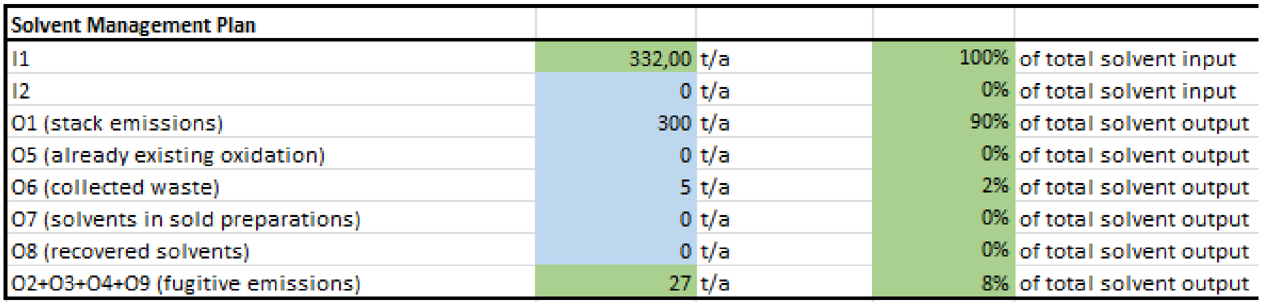
| | | Laminating | | |
|---|---|---|---|---|
| *Undiluted products* | | | | |
| Product input (undiluted products, as bought) | | | 80 | t/a |
| Solid content | 20 | t/a | 25 | wt.-% of undiluted inks |
| Solvent content of undiluted products | 40 | t/a | 50 | wt.-% of undiluted inks |
| Other contents of undiluted products (e.g. water) | 20 | t/a | 25 | wt.-% of undiluted inks |
| *Ready-to-use products* | | | | |
| Additional solvents for dilution | | | 10 | t/a |
| Solvent content of ready-to-use products | | | 50 | t/a |
| Additional solvents for cleaning etc. | | | 2 | t/a |

The following summary table shows the total solvent and solid inputs into the plant and thus characterizes the original plant without any measures.



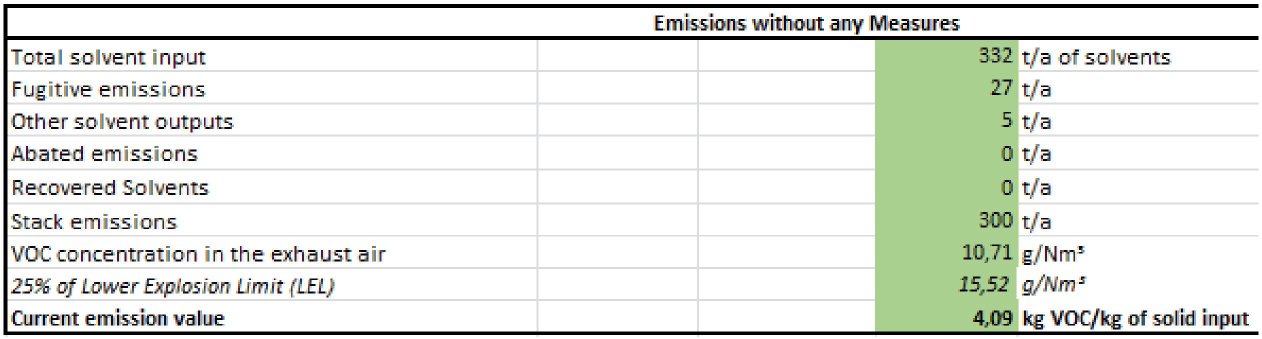
| | | | Summary | |
|---|---|---|---|---|
| Total solvents in ready-to-use product | | | 320 | t/a |
| Total solvents in product bought | | | 130 | t/a |
| Total solvents for further dilution | | | 190 | t/a |
| Total solvents for cleaning | | | 12 | t/a |
| Solid input | | | 80 | t/a |
| **Total solvent input** | | | 332 | **t/a** |
| VOC factor | | | 4,15 | kg VOC/kg solid input |

By determining the input and output streams of solvents, the Solvent Management Plan (SMP) is derived. The exemplary values are provided below:



| **Solvent Management Plan** | | | | |
|---|---|---|---|---|
| I1 | 332,00 | t/a | 100% | of total solvent input |
| I2 | 0 | t/a | 0% | of total solvent input |
| O1 (stack emissions) | 300 | t/a | 90% | of total solvent output |
| O5 (already existing oxidation) | 0 | t/a | 0% | of total solvent output |
| O6 (collected waste) | 5 | t/a | 2% | of total solvent output |
| O7 (solvents in sold preparations) | 0 | t/a | 0% | of total solvent output |
| O8 (recovered solvents) | 0 | t/a | 0% | of total solvent output |
| O2+O3+O4+O9 (fugitive emissions) | 27 | t/a | 8% | of total solvent output |

Thereof, the emissions without any abatement measures can already be calculated:



| | | | Emissions without any Measures | |
|---|---|---|---|---|
| Total solvent input | | | 332 | t/a of solvents |
| Fugitive emissions | | | 27 | t/a |
| Other solvent outputs | | | 5 | t/a |
| Abated emissions | | | 0 | t/a |
| Recovered Solvents | | | 0 | t/a |
| Stack emissions | | | 300 | t/a |
| VOC concentration in the exhaust air | | | 10,71 | $g/Nm^3$ |
| *25% of Lower Explosion Limit (LEL)* | | | *15,52* | *$g/Nm^3$* |
| **Current emission value** | | | **4,09** | **kg VOC/kg of solid input** |

The current emission value shows that without VOC abatement the required ELV of 0,5 kg VOC/kg of solid input cannot be achieved. Abatement measures are thus necessary for this installation.

Thus, the consumption data of the considered processes after product replacement have to be provided. In this case, this is only relevant for the laminating process, as the solvent-based adhesives shall be replaced by a 100% solid adhesive.[11]

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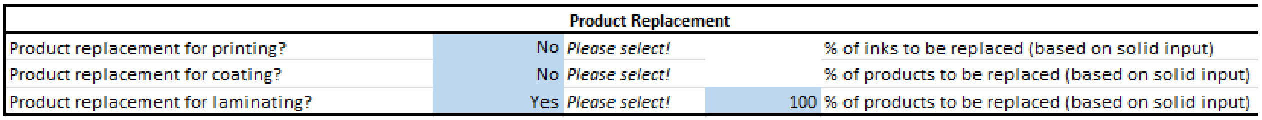
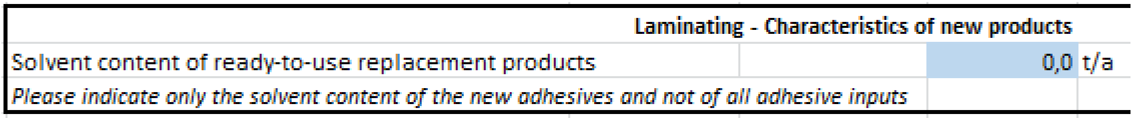
[11] The applicability of 100%-solid adhesives needs to be checked first, based on the product specifications and quality requirements and the machinery that is in use.



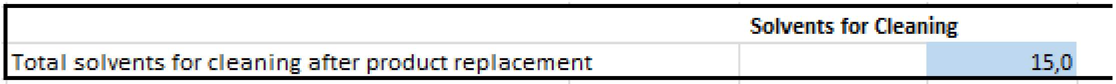
| Product Replacement | | | | |
|---|---|---|---|---|
| Product replacement for printing? | No | *Please select!* | | % of inks to be replaced (based on solid input) |
| Product replacement for coating? | No | *Please select!* | | % of products to be replaced (based on solid input) |
| Product replacement for laminating? | Yes | *Please select!* | 100 | % of products to be replaced (based on solid input) |

In this case, the whole lamination process is to be modified, which means that 100% of adhesives will be replaced. In other cases, it might be for example only one of several production lines that will be equipped with new products while other lines are continued to be operated with the current products. Thus the percentage of products to be replaced is lower.



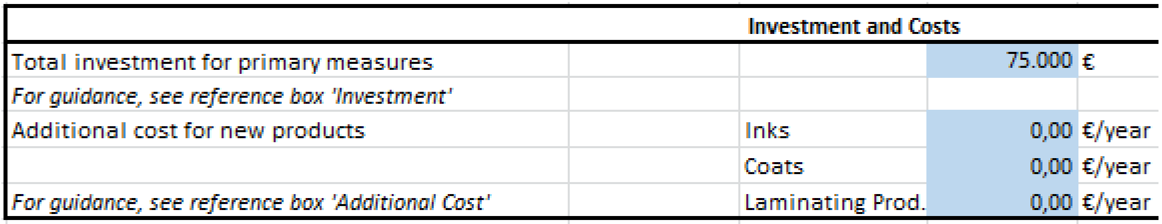
| | Laminating - Characteristics of new products | |
|---|---|---|
| Solvent content of ready-to-use replacement products | 0,0 | t/a |
| *Please indicate only the solvent content of the new adhesives and not of all adhesive inputs* | | |

Apart from the solvent content of the replacing products, variations in the solvent demand for cleaning can be considered as well.



| | Solvents for Cleaning |
|---|---|
| Total solvents for cleaning after product replacement | 15,0 |

In the next step, the investment for primary measures has to be inserted. We assume a reference value of 75.000 € per product to be replaced.[12] As we modify only the lamination process, we consider this sufficient. We do not consider any additional cost or savings for the new product, as 100%-solid adhesives are usually very economic, yet we do not have specific cost data in order to compare the cost of solvent-based and 100%-solid products. Therefore we expect the total cost to be rather over than underestimated.



| | | Investment and Costs | |
|---|---|---|---|
| Total investment for primary measures | | 75.000 | € |
| *For guidance, see reference box 'Investment'* | | | |
| Additional cost for new products | Inks | 0,00 | €/year |
| | Coats | 0,00 | €/year |
| *For guidance, see reference box 'Additional Cost'* | Laminating Prod. | 0,00 | €/year |

The following table shows the emission statistics after implementation of the primary measures, with the specific emissions to air still exceeding the ELV.

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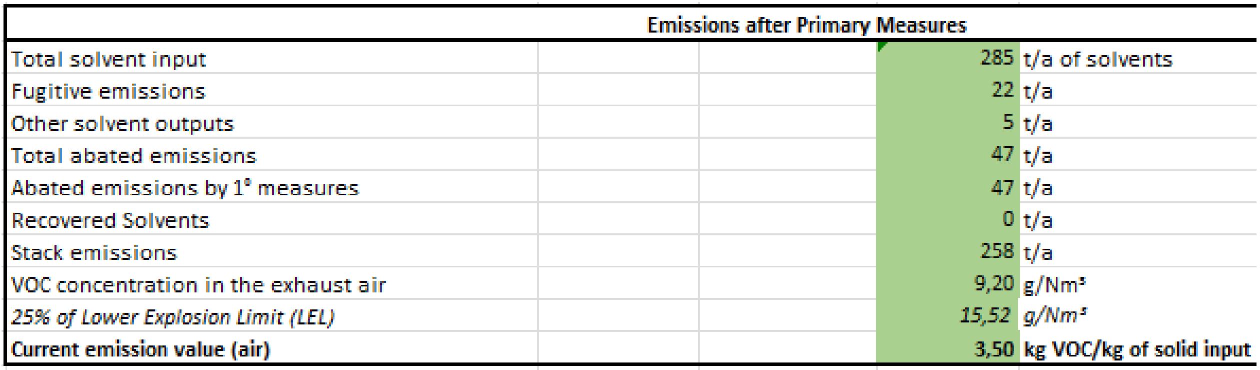
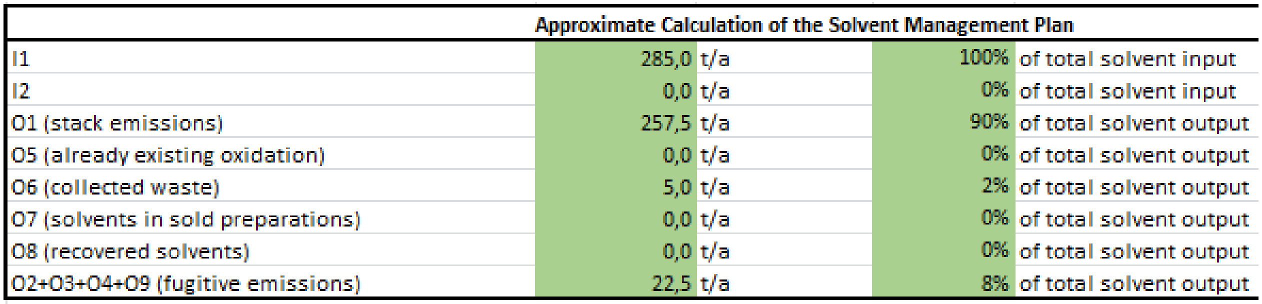
[12] „per product" means per ink, adhesive, coat, etc. as the replacement causes efforts and costs for testing, configurating the machines, minor technical modifications of machines, etc. This effort is expected to occur for every product to be replaced.



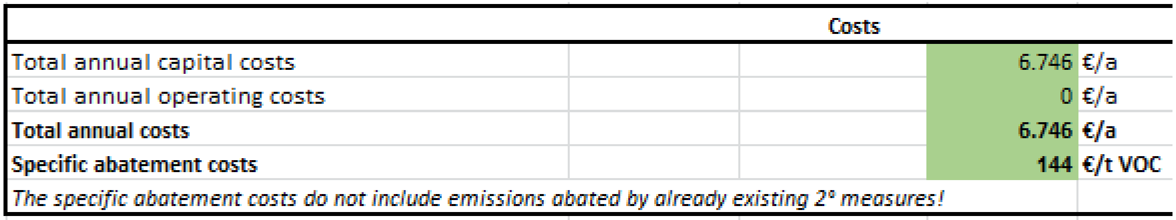
| Emissions after Primary Measures | | |
|---|---|---|
| Total solvent input | 285 | t/a of solvents |
| Fugitive emissions | 22 | t/a |
| Other solvent outputs | 5 | t/a |
| Total abated emissions | 47 | t/a |
| Abated emissions by 1° measures | 47 | t/a |
| Recovered Solvents | 0 | t/a |
| Stack emissions | 258 | t/a |
| VOC concentration in the exhaust air | 9,20 | g/Nm³ |
| *25% of Lower Explosion Limit (LEL)* | *15,52* | *g/Nm³* |
| **Current emission value (air)** | **3,50** | **kg VOC/kg of solid input** |

The resulting solvent management plan after primary measures is provided below.



| Approximate Calculation of the Solvent Management Plan | | | | |
|---|---|---|---|---|
| I1 | 285,0 | t/a | 100% | of total solvent input |
| I2 | 0,0 | t/a | 0% | of total solvent input |
| O1 (stack emissions) | 257,5 | t/a | 90% | of total solvent output |
| O5 (already existing oxidation) | 0,0 | t/a | 0% | of total solvent output |
| O6 (collected waste) | 5,0 | t/a | 2% | of total solvent output |
| O7 (solvents in sold preparations) | 0,0 | t/a | 0% | of total solvent output |
| O8 (recovered solvents) | 0,0 | t/a | 0% | of total solvent output |
| O2+O3+O4+O9 (fugitive emissions) | 22,5 | t/a | 8% | of total solvent output |

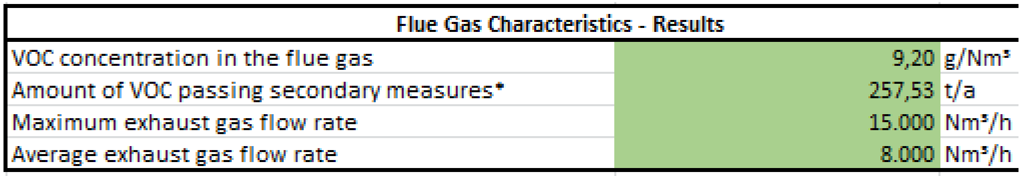
The specific abatement costs of primary measures can be calculated by annualizing the investment expenses.



| Costs | | |
|---|---|---|
| Total annual capital costs | 6.746 | €/a |
| Total annual operating costs | 0 | €/a |
| **Total annual costs** | **6.746** | **€/a** |
| **Specific abatement costs** | **144** | **€/t VOC** |
| *The specific abatement costs do not include emissions abated by already existing 2° measures!* | | |

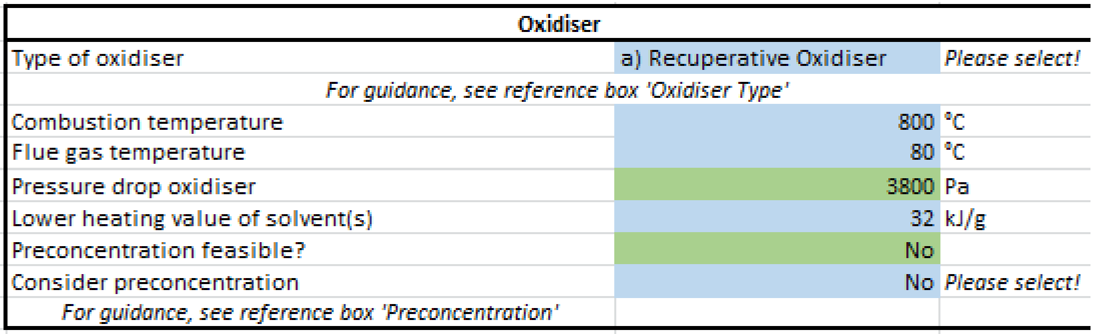
### 7.4.2 Secondary Measures (Oxidation)

For the calculation of secondary measures, the maximal and the average exhaust gas flow rate are of interest. They have been provided already to calculate the VOC concentrations in the flue gas in the primary measure calculation. Now the two values need to be distinguished, as for design parameters, the maximal flow rate is relevant and for consumption parameters it is the annual average value that is important. The resulting VOC concentration has been checked in order to be below the 25% of the lower explosion limit threshold in the flue gas.



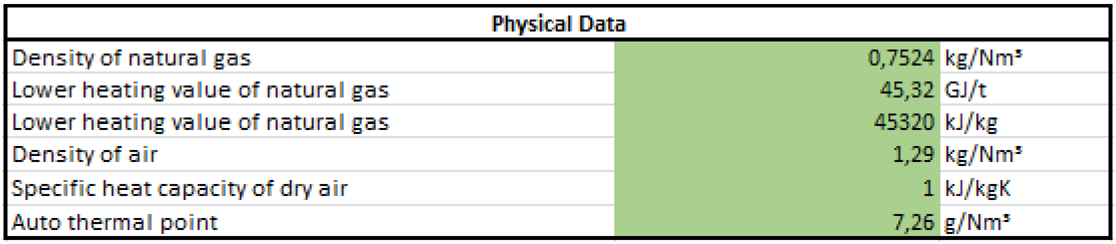
| Flue Gas Characteristics - Results | | |
|---|---|---|
| VOC concentration in the flue gas | 9,20 | g/Nm³ |
| Amount of VOC passing secondary measures* | 257,53 | t/a |
| Maximum exhaust gas flow rate | 15.000 | Nm³/h |
| Average exhaust gas flow rate | 8.000 | Nm³/h |

The following oxidiser parameters are necessary in order to calculate the investment and energy consumption of the oxidiser. We consider a recuperative oxidiser that is operated above the auto thermal point (ATP), preconcentration shall not be considered.

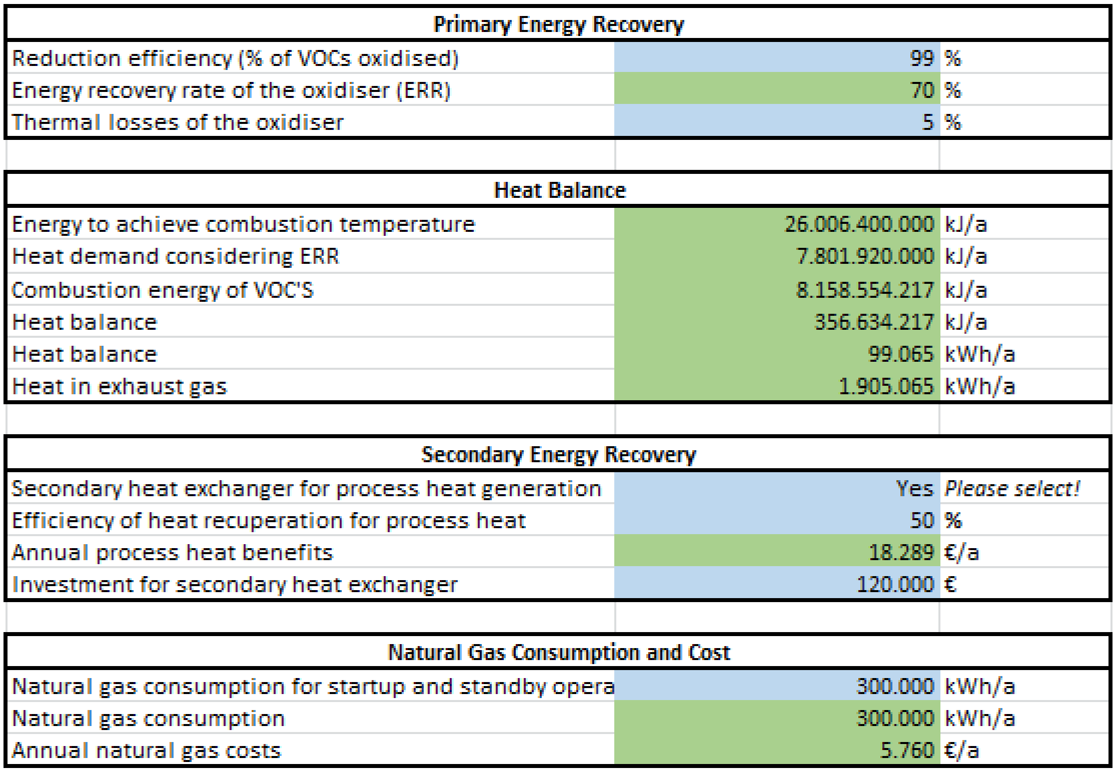


| Oxidiser | | |
|---|---|---|
| Type of oxidiser | a) Recuperative Oxidiser | *Please select!* |
| *For guidance, see reference box 'Oxidiser Type'* | | |
| Combustion temperature | 800 | °C |
| Flue gas temperature | 80 | °C |
| Pressure drop oxidiser | 3800 | Pa |
| Lower heating value of solvent(s) | 32 | kJ/g |
| Preconcentration feasible? | No | |
| Consider preconcentration | No | *Please select!* |
| *For guidance, see reference box 'Preconcentration'* | | |

The calculation of the auto thermal point is automatically performed by the tool based on various physical properties and oxidiser characteristics.



| Physical Data | | |
|---|---|---|
| Density of natural gas | 0,7524 | kg/Nm³ |
| Lower heating value of natural gas | 45,32 | GJ/t |
| Lower heating value of natural gas | 45320 | kJ/kg |
| Density of air | 1,29 | kg/Nm³ |
| Specific heat capacity of dry air | 1 | kJ/kgK |
| Auto thermal point | 7,26 | g/Nm³ |



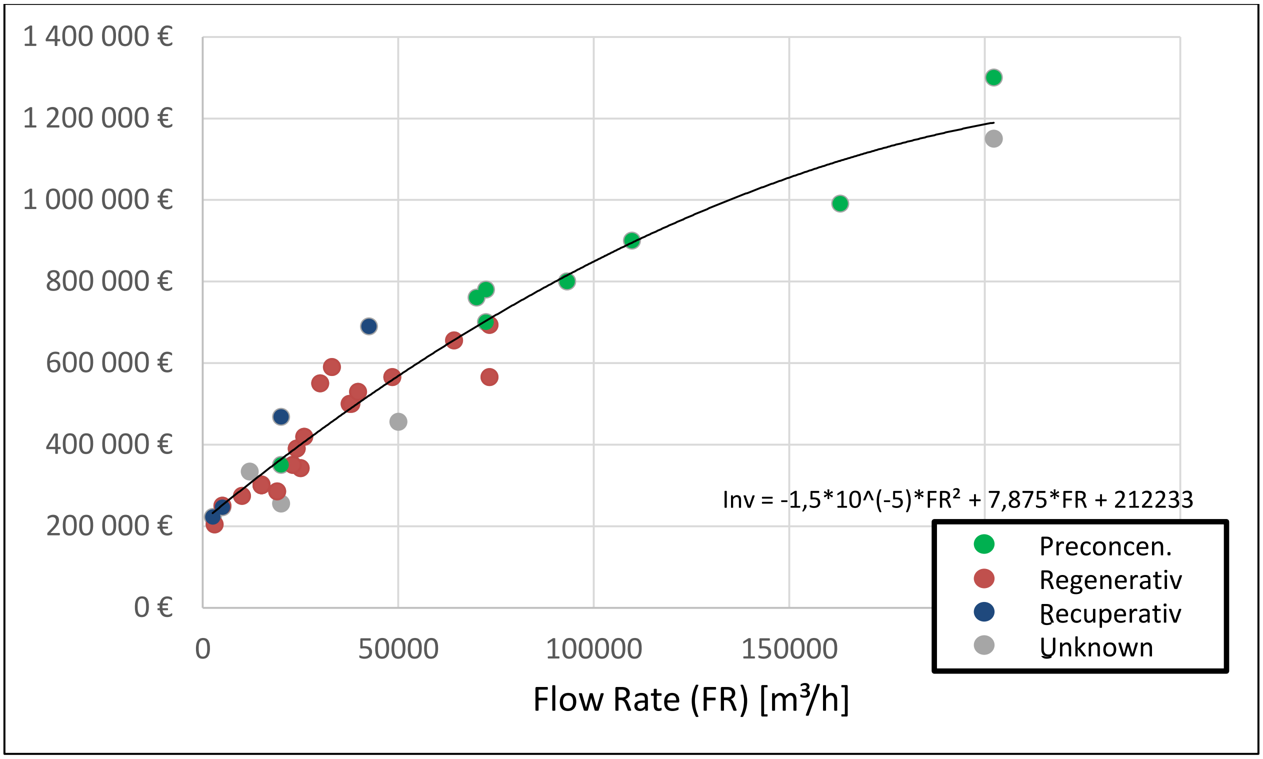
| Primary Energy Recovery | | |
|---|---|---|
| Reduction efficiency (% of VOCs oxidised) | 99 | % |
| Energy recovery rate of the oxidiser (ERR) | 70 | % |
| Thermal losses of the oxidiser | 5 | % |

| Heat Balance | | |
|---|---|---|
| Energy to achieve combustion temperature | 26.006.400.000 | kJ/a |
| Heat demand considering ERR | 7.801.920.000 | kJ/a |
| Combustion energy of VOC'S | 8.158.554.217 | kJ/a |
| Heat balance | 356.634.217 | kJ/a |
| Heat balance | 99.065 | kWh/a |
| Heat in exhaust gas | 1.905.065 | kWh/a |

| Secondary Energy Recovery | | |
|---|---|---|
| Secondary heat exchanger for process heat generation | Yes | *Please select!* |
| Efficiency of heat recuperation for process heat | 50 | % |
| Annual process heat benefits | 18.289 | €/a |
| Investment for secondary heat exchanger | 120.000 | € |

| Natural Gas Consumption and Cost | | |
|---|---|---|
| Natural gas consumption for startup and standby opera | 300.000 | kWh/a |
| Natural gas consumption | 300.000 | kWh/a |
| Annual natural gas costs | 5.760 | €/a |

The tables above show the calculation of the energy balance within the oxidiser. Therefore, the heat balance needs to be set up and the natural gas consumption can be calculated thereof. It is important to mention that even though the oxidiser is operated in auto-thermal mode, natural gas is necessary for start-up and shut-down processes and standby operation. The amount of energy needed is primarily depending on the mode of operation of the plant.



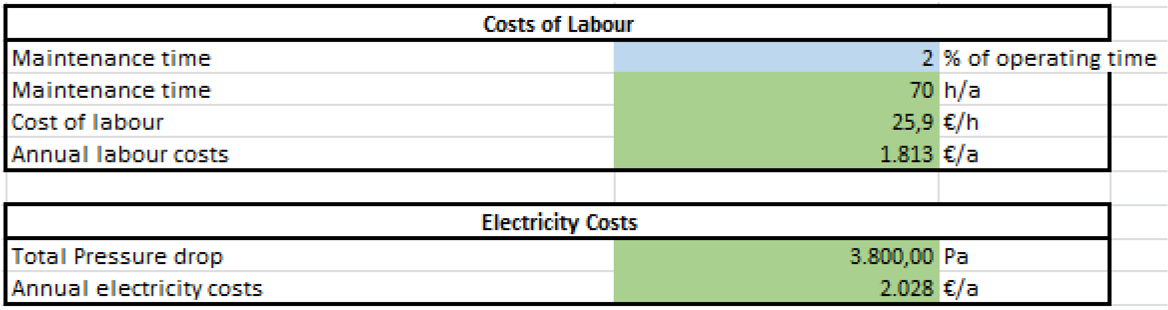
The graph above shows the investment curve for oxidisers that has been developed based on a broad variety of exemplary data from industry representatives and scientific publications. In the table below, the resulting investment for the considered case is provided. Ab hier prüfen

| **Investment** | | |
|---|---|---|
| Investment | 326.983 | € |
| Factor for installation expenditure | 1,85 | |
| *For guidance, see reference box* | | |
| Secondary heat exchanger | 120.000 | € |
| **Total investment** | **724.919** | **€** |

The fixed operating costs are derived thereof:

| **Insurance and Taxes** | | |
|---|---|---|
| Percentage of total investment | 3 | % |
| Annual insurance and tax cost | 21.748 | €/a |
| | | |
| **Repair and Maintenance** | | |
| Percentage of total investment | 3 | % |
| Annual maintenance cost (without labour) | 21.748 | €/a |

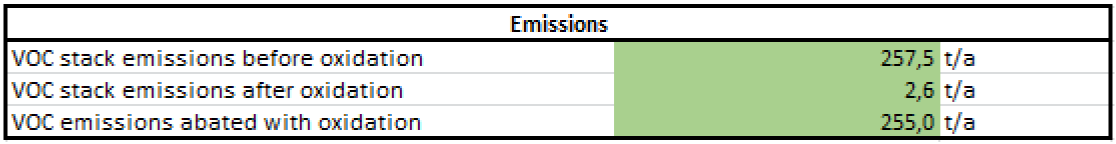
The variable operating costs are calculated as follows.



| Costs of Labour | | |
|---|---|---|
| Maintenance time | 2 | % of operating time |
| Maintenance time | 70 | h/a |
| Cost of labour | 25,9 | €/h |
| Annual labour costs | 1.813 | €/a |

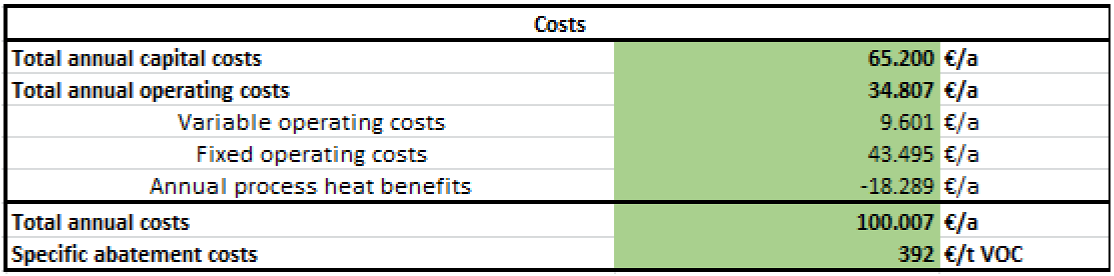
| Electricity Costs | | |
|---|---|---|
| Total Pressure drop | 3.800,00 | Pa |
| Annual electricity costs | 2.028 | €/a |

The emissions after oxidation can be derived of the reduction efficiency provided above.



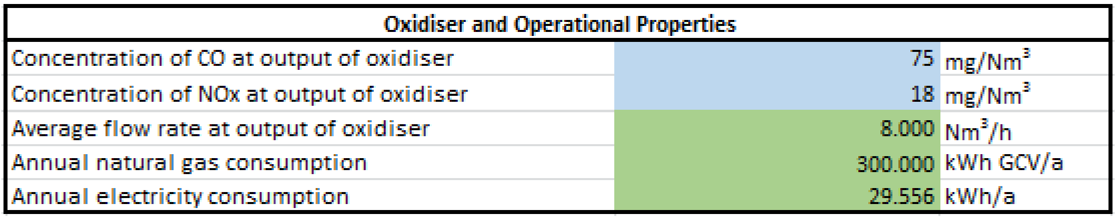
| Emissions | | |
|---|---|---|
| VOC stack emissions before oxidation | 257,5 | t/a |
| VOC stack emissions after oxidation | 2,6 | t/a |
| VOC emissions abated with oxidation | 255,0 | t/a |

The following table summarizes the annual and specific costs for oxidation, considering capital and operating costs as well as process heat benefits (if applicable).

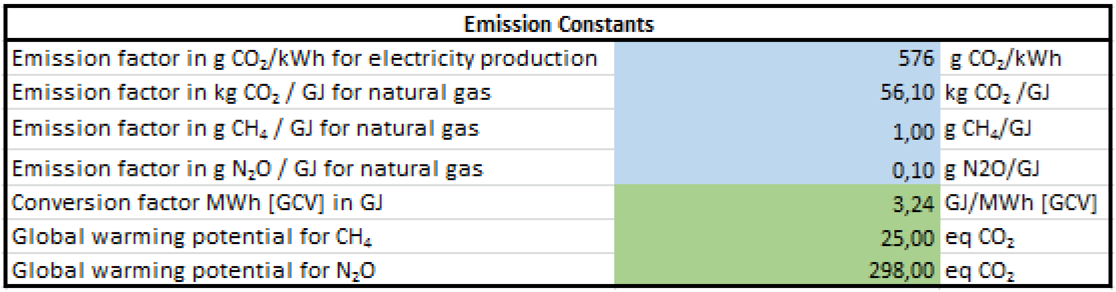


| Costs | | |
|---|---|---|
| **Total annual capital costs** | **65.200** | **€/a** |
| **Total annual operating costs** | **34.807** | **€/a** |
| Variable operating costs | 9.601 | €/a |
| Fixed operating costs | 43.495 | €/a |
| Annual process heat benefits | -18.289 | €/a |
| **Total annual costs** | **100.007** | **€/a** |
| **Specific abatement costs** | **392** | **€/t VOC** |

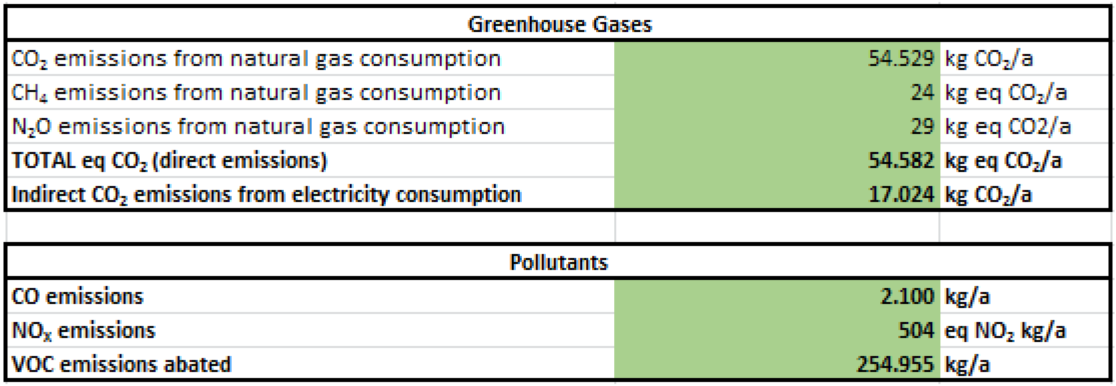
Even though the aim of an oxidiser is abating emissions, some other emissions are generated by installing a thermal oxidation. These are primarily greenhouse gases formed during the combustion process. These emissions need to be considered in order to get a complete picture of the emission situation after installing a thermal oxidiser. For the given example, the calculations and results are provided below:



| Oxidiser and Operational Properties | | |
|---|---|---|
| Concentration of CO at output of oxidiser | 75 | $mg/Nm^3$ |
| Concentration of NOx at output of oxidiser | 18 | $mg/Nm^3$ |
| Average flow rate at output of oxidiser | 8.000 | $Nm^3/h$ |
| Annual natural gas consumption | 300.000 | kWh GCV/a |
| Annual electricity consumption | 29.556 | kWh/a |



| Emission Constants | | |
|---|---|---|
| Emission factor in g $CO_2$/kWh for electricity production | 576 | g $CO_2$/kWh |
| Emission factor in kg $CO_2$ / GJ for natural gas | 56,10 | kg $CO_2$ /GJ |
| Emission factor in g $CH_4$ / GJ for natural gas | 1,00 | g $CH_4$/GJ |
| Emission factor in g $N_2O$ / GJ for natural gas | 0,10 | g N2O/GJ |
| Conversion factor MWh [GCV] in GJ | 3,24 | GJ/MWh [GCV] |
| Global warming potential for $CH_4$ | 25,00 | eq $CO_2$ |
| Global warming potential for $N_2O$ | 298,00 | eq $CO_2$ |

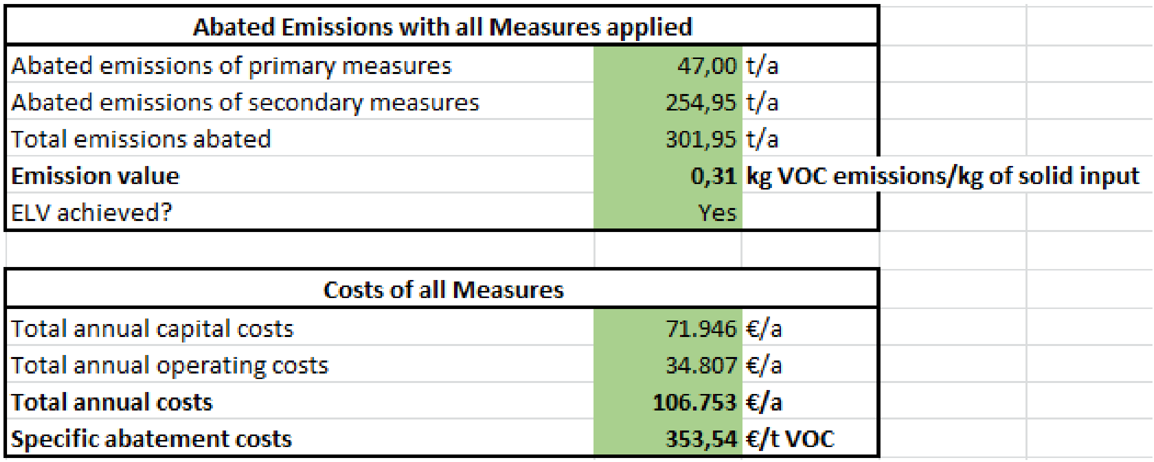


| Greenhouse Gases | | |
|---|---|---|
| $CO_2$ emissions from natural gas consumption | 54.529 | kg $CO_2$/a |
| $CH_4$ emissions from natural gas consumption | 24 | kg eq $CO_2$/a |
| $N_2O$ emissions from natural gas consumption | 29 | kg eq CO2/a |
| **TOTAL eq $CO_2$ (direct emissions)** | **54.582** | **kg eq $CO_2$/a** |
| **Indirect $CO_2$ emissions from electricity consumption** | **17.024** | **kg $CO_2$/a** |

| Pollutants | | |
|---|---|---|
| **CO emissions** | **2.100** | **kg/a** |
| **$NO_x$ emissions** | **504** | **eq $NO_2$ kg/a** |
| **VOC emissions abated** | **254.955** | **kg/a** |

### 7.4.3 Summary

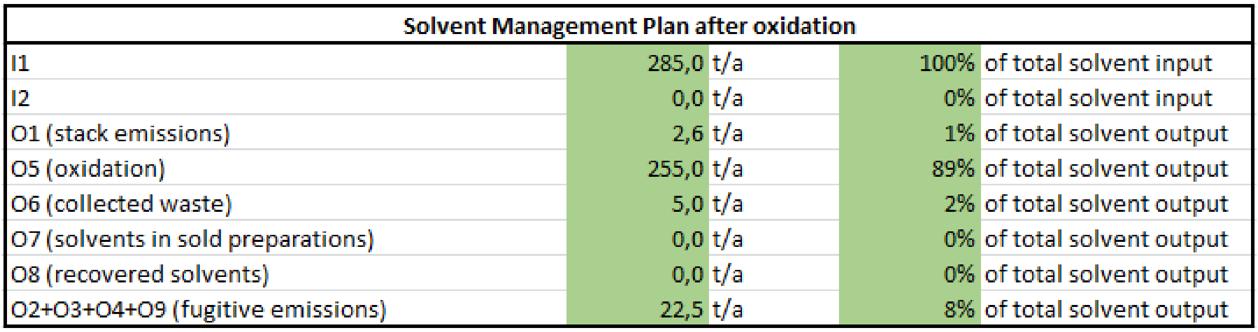
The following tables provide an overview of all measures applied. The emission calculation shows that the ELV is now achieved with a total emission value of 0,31 kg VOC emissions per kg solid input. The emissions without any measures were 4,15 kg VOC emissions per kg of solid input. Therefore an emission reduction of 92,5% has been achieved.



| Abated Emissions with all Measures applied | | |
|---|---|---|
| Abated emissions of primary measures | 47,00 | t/a |
| Abated emissions of secondary measures | 254,95 | t/a |
| Total emissions abated | 301,95 | t/a |
| **Emission value** | **0,31** | **kg VOC emissions/kg of solid input** |
| ELV achieved? | Yes | |

| Costs of all Measures | | |
|---|---|---|
| Total annual capital costs | 71.946 | €/a |
| Total annual operating costs | 34.807 | €/a |
| **Total annual costs** | **106.753** | **€/a** |
| **Specific abatement costs** | **353,54** | **€/t VOC** |

The specific abatement costs for all measures sum up to 319€ t/VOC abated and finally the resulting SMP for this exemplary calculation is provided below.

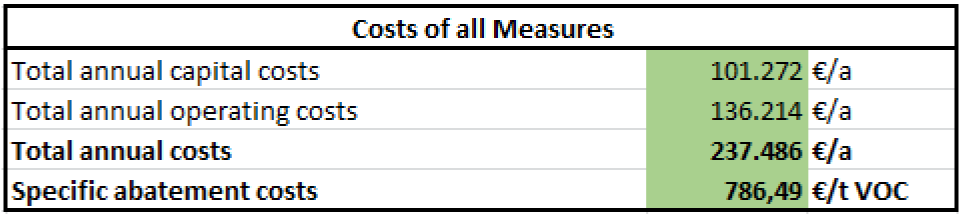


| Solvent Management Plan after oxidation | | | | |
|---|---|---|---|---|
| I1 | 285,0 | t/a | 100% | of total solvent input |
| I2 | 0,0 | t/a | 0% | of total solvent input |
| O1 (stack emissions) | 2,6 | t/a | 1% | of total solvent output |
| O5 (oxidation) | 255,0 | t/a | 89% | of total solvent output |
| O6 (collected waste) | 5,0 | t/a | 2% | of total solvent output |
| O7 (solvents in sold preparations) | 0,0 | t/a | 0% | of total solvent output |
| O8 (recovered solvents) | 0,0 | t/a | 0% | of total solvent output |
| O2+O3+O4+O9 (fugitive emissions) | 22,5 | t/a | 8% | of total solvent output |

## 7.5 Uncertainties and Critical Acclaim

The example above provides a calculation for a very specific example. This can be regarded as a rather optimistic example, as there is secondary heat recovery considered and the operating time is comparably high, while the flow rate is low, which leads to a high VOC concentration and thus an efficient operation of the oxidator.

If the maximum flow rate is raised to 40.000 Nm³/h with an average flow rate of 20.000 Nm³/h and secondary heat recovery is not considered, the specific abatement costs for the same emission abatement are more than doubled, as shown below.



| Costs of all Measures | | |
|---|---|---|
| Total annual capital costs | 101.272 | €/a |
| Total annual operating costs | 136.214 | €/a |
| **Total annual costs** | **237.486** | **€/a** |
| **Specific abatement costs** | **786,49** | **€/t VOC** |

These two numbers can be considered as good and bad case examples. Further plant specific calculations are of course necessary in order to understand the specific circumstances of a plant. In this case, for example, a reduced number of operating hours (e.g. 11 months, 20 days per month, 8 hours per day – 1760 hours per year in total) with constant consumption rates would lead to a moderate cost decrease with resulting specific abatement costs of 603,90 €. More examples and understanding of the main cost drivers can be gained by using ERICCa_VOC based on the example above or a plant specific example if applicable.

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