TFTEI

TASK FORCE ON TECHNO ECONOMIC ISSUES

ESTIMATION OF COSTS OF REDUCTION TECHNIQUES FOR VOC-REDUCTION IN PACKAGING PRINTING AND OTHER ACTIVITIES

TFTEI Technical Secretariat

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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 often refers to EGTEI, but this designates TFTEI from now.

Content

Preamble/Foreword

TFTEI (Task Force on Techno-Economic Issues), established in December 2014 (previously known as EGTEI, Expert Group on Techno-Economic Issues, established in 2001), is mandated by the UNECE in the scope of the CLRTAP, with the goal to develop technical and economic data for air pollution abatement techniques for stationary and mobiles sources.

The methodology for cost estimation of abatement options for VOC (Volatile Organic Compounds) has been developed for installations in the automotive and the packaging printing sector with a solvent input of more than 200 tons per year.

However, the design and costs of VOC reduction measures are similar for many other sectors with comparable operating conditions. The tool is therefore expected to be broadly applicable, even though it has not been validated for other sectors.

The methodology presented hereafter, aims at providing cost data for primary measures (substitution of products with high solvent content) and the secondary measures thermal oxidation and adsorption with solvent recovery.

Costs are estimated for different regulatory objectives based on the solvent management plan methodology. A detailed explanation of the solvent management plan is provided for example in [UNECE, 2015].

1 Structure of the document

ERICCa_VOC is a Microsoft Excel based tool to calculate costs and performance parameters of VOC abatement measures in large VOC processing installations of the automotive and the packaging printing sector.

The Excel document consists of four worksheets, one for the primary measures, two for secondary measures (oxidation and adsorption with solvent recovery) and a summary page. The calculations are based on a broad variety of input data that has to be provided by the user. Cells for user input are always marked in blue, whereas cells with calculation results are marked in green. Only blue cells are to be adapted by the user, as inputs in the green cells threaten the correctness of all subsequent calculations. For some parameters, reference boxes are available in order to support the gathering of data or to provide reference values.

			Colour guide
Interest rate	4,00	%	Result
Lifetime	15	a	Input Data
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	

Figure 1: Exemplary input and calculation cells in ERICCa_VOC

The following document is structured according to ERICCa_VOC itself. After an introduction it starts with primary measures, followed by secondary measures and the summary in the end.

2 Principles of cost estimation

The methodology developed for estimating costs of VOC abatement aims at being as consistent and transparent as possible. To support the comparability of data, cost components are clearly stated. As far as possible, recommendations of the Reference document on Economic and Cross Media Effects of the European Commission [EU Commission, 2006b] are taken into account. For estimating costs, recent literature data and industry information from plant operators and equipment suppliers are considered.

1.1 Composition of costs

The total annual costs, $\dot{C}_{tot}$ as well as the specific annual costs for abating the pollutant i $C_{tot,spec,i.}$ are essential in the assessment process of EU BAT (Best Available Techniques). They are thus defined in equations 2-1 and 2-2:

$$\dot{C}_{tot}\left[\frac{€}{year}\right] = \dot{C}_{cap}\left[\frac{€}{year}\right] + \dot{C}_{op}\left[\frac{€}{year}\right]$$	2-1
$$C_{tot,spec,i.}\left[\frac{€}{mass\ abated}\right] = \left(\dot{C}_{tot}\left[\frac{€}{year}\right]\right) \cdot \left(\dot{m}_{i,year}\right)^{-1}\left[\frac{year}{mass\ abated}\right]$$	2-2

In case of VOC abatement, the total specific abatement costs per mass of VOC are calculated by dividing the total annual cost by the mass of abated VOC $\dot{m}_{VOC,year}$, usually metric tons or kilograms.

2.1.1 Capital costs

Literature data on investments rarely provides details on the components taken into account, so that comparisons are difficult. Investment for VOC control equipment and installation expenditure including permits, insurance, contingency etc. is usually calculated without taxes as they are expected to vary in an international context.

For calculating capital costs at an annual level, the costs of the initial investment need to be spread onto the years of operation. The annualised capital cost can be calculated according to equation 2-3 with the parameters *p* (interest rate) and *n* (technical or economic lifetime of the equipment):

$$\dot{C}_{cap}\left[\frac{€}{year}\right] = Invest \cdot \frac{(1+p)^n}{(1+p)^n - 1} \cdot p \qquad \text{2-3}$$

In case of unknown lifetime of the control equipment, the lifetime is assumed to equal the lifetime of the overall plant.

2.1.2 Operating costs

Total annual operating costs consist of fixed and variable operating costs and can consider benefits (e.g. heat recovery for external processes), as shown in equation 2-4:

$$\dot{C}_{op}\left[\frac{€}{year}\right] = \dot{C}_{op,fix}\left[\frac{€}{year}\right] + \dot{C}_{op,var}\left[\frac{€}{year}\right] - \dot{B}_{op}\left[\frac{€}{year}\right] \qquad \text{2-4}$$

The annual fixed operating costs $\dot{C}_{op,fix}$ are usually calculated as a percentage of the unit investment and costs such as maintenance, insurance, wages[1], etc. are covered therein.

Variable operating costs $\dot{C}_{op,var}$ contain costs for utilities such as electricity, as described in equation 2-5. :

$$\dot{C}_{var}\left[\frac{€}{year}\right] = \Sigma \dot{C}_{var}^{unit}\left[\frac{€}{year}\right], \text{ unit} \in \{\text{electricity, vapour, carbon, natural gas, catalysts, etc.}\} \qquad \text{2-5}$$

Benefits from the reduction process B_{op} represent financial gains from recovered products or recovered energy. They are calculated in analogy to the variable operating costs, with respect to

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[1] It was the objective of the EGTEI technical secretariat to specify wage costs independently, when the revision of the cost methodology started. The working group decided to follow the common rules and include them in fixed operating costs finally due to lack of data.

the algebraic sign (in eq. 2-4, benefits are subtracted; therefore, they have to be calculated as a positive value).

2.2 Time and currency conversion

As reference data may be several years old or from a different country/region with differing currency, conversions may be necessary to align the reference data with the considered investment project.

2.2.1 Conversion of currency differences

Currency conversion from literature values in foreign currencies to Euro are done at the reported conversion rates and stated explicitly. If no currency conversion rate was provided, the annual average of the conversion rate in the regarded year was used. This procedure is also recommended for conversions of user specific data, if necessary.

2.2.2 Temporal adaptation

Investment and costs cannot be compared without integrating temporal aspect due to inflation, technical and market developments. To enable the comparison of costs or investments from different years, various indices have been developed. One of these indices, the Chemical Engineering Plant Cost Index (CEPCI), will be used in this document for temporal adaptations (cf. Table 1). The investments and costs in this document are expressed in EUR 2014:

Table 1: Cost elevation factors derived from CEPCI (Chemical Engineering 2017)

Cost year	Factor	CEPCI Value	Cost year	Factor	CEPCI Value
2016	1,00	541,7	2006	1,08	499,6
2015	0,97	556,8	2005	1,16	468,2
2014	0,94	576,1	2004	1,22	444,2
2013	0,95	567,3	2003	1,35	401,7
2012	0,93	584,6	2002	1,37	395,6
2011	0,92	585,7	2001	1,37	394,3
2010	0,98	550,8	2000	1,37	394,1
2009	1,04	521,9	1999	1,39	390,6
2008	0,94	575,4	1998	1,39	389,5
2007	1,03	525,4	1997	1,40	386,5

2.3 Utility costs

Table 2 displays the reference net utility prices provided for calculating the operating costs of the pollutant abatement techniques. They can be updated according to the needs of the user, if better data is available.

Table 2: Default utility costs

Utility		Price	Unit
Electricity	c_{elec}	0,07	€/kWh
Price of Process Heat	$c_{processheat}$	0,025	€/kWh
Price of Natural Gas	$c_{naturalgas}$	0,025	€/kWh
Price of Vapour	c_{vapour}	0,016	€/kg
Price of Nitrogen	$c_{nitrogen}$	2,00	€/kg
Costs of Activated Carbon	c_{carbon}	3,00	€/kg
Price of Solvents replaced by recovered Solvents		0,15	€/kg
Selling-Price of recovered Solvents		0,10	€/kg

3 Emission loads

The estimation of VOC emissions in ERICCa_VOC is divided in three steps. The worksheet 'Primary Measures' contains the initial situation and the primary measures product replacement and organizational improvements. As secondary measures, oxidation or adsorption with solvent recovery can be selected. Finally, a summary page derives the overall VOC emissions and costs of all considered measures. The worksheets of the secondary measures can also be used independently of the primary measures. A more detailed description of the possible applications will be provided in the following. ERICCa_VOC enables an estimation of the current and the attainable VOC emission loads depending on the solvent consumption, abatement techniques and the solvent management plan.

3.1 Solvent consumption

Three VOC consuming processes, printing, coating and laminating, can be considered in ERICCa_VOC. They can be selected individually, i.e. all combinations of processes are possible. After selecting the processes, the product information has to be provided for every process. Therefore, the total amount of undiluted product, the solid content and the solvent content of the products need to be provided as well as additional solvents needed for further dilution and cleaning. Thereof, the total solvent and solid input is calculated. Equation 3-1 displays the

calculation of the annual solvent content of the ready to use products. It considers the solvents in products and solvents for further dilution for all considered processes p. Equation 3-2 displays the similar calculation for the cleaning solvents and 3-3 for the solid input. The solid content of products is a good target value to compare the necessary amount of different products as the solid content needed to treat a surface is usually the same for different products[2]. Equation 3-4 sums up the total solvent input of all considered processes.

$$m_{r2u\,product}^{solvent}\left[\frac{t}{year}\right] = \sum_{p} m_{r2u\,product,p}^{solvent}\left[\frac{t}{year}\right]$$	3-1
$$m_{cleaning}^{solvent}\left[\frac{t}{year}\right] = \sum_{p} m_{cleaning,p}^{solvent}\left[\frac{t}{year}\right]$$	3-2
$$m^{solid}\left[\frac{t}{year}\right] = \sum_{p} m^{solid}\left[\frac{t}{year}\right]$$	3-3
$$m_{total}^{solvent}\left[\frac{t}{year}\right] = m_{r2u\,product}^{solvent}\left[\frac{t}{year}\right] + m_{cleaning}^{solvent}\left[\frac{t}{year}\right]$$	3-4
$$F_{VOC}\left[\frac{t\,VOC}{t\,solid\,input}\right] = \frac{m_{total}^{solvent}\left[\frac{t}{year}\right]}{m^{solid}\left[\frac{t}{year}\right]}$$	3-5

The VOC factor (F_{VOC}) is calculated in 3-5. It does not consider any abatement measures and a reduction can thus only be achieved by primary measures. For secondary measures, the emission factor will be calculated separately, in order to distinguish the solvent input from the solvent output of a plant.

3.2 Solvent management and emissions

Based on the UNECE recommendation, the integrated assessment of solvent emissions in ERICCa_VOC is based on the solvent management plan (SMP). An illustrative example with all relevant input and output streams is provided in Figure 2.

Three stages of the SMP are considered in ERICCa_VOC. The initial SMP, the SMP after primary measures (including product replacement and organizational measures, such as encapsulation, waste reduction, etc.) and the SMP after secondary measures. The initial SMP needs to be provided in the worksheet 'primary'. A screenshot thereof is displayed in Figure 3. The blue cells are to be filled in by the user while the green cells are calculated automatically.

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[2] As the VOC and other solvents such as water evaporate during the drying of the products, the solid content is the final coat that is meant to stay on the base layers.
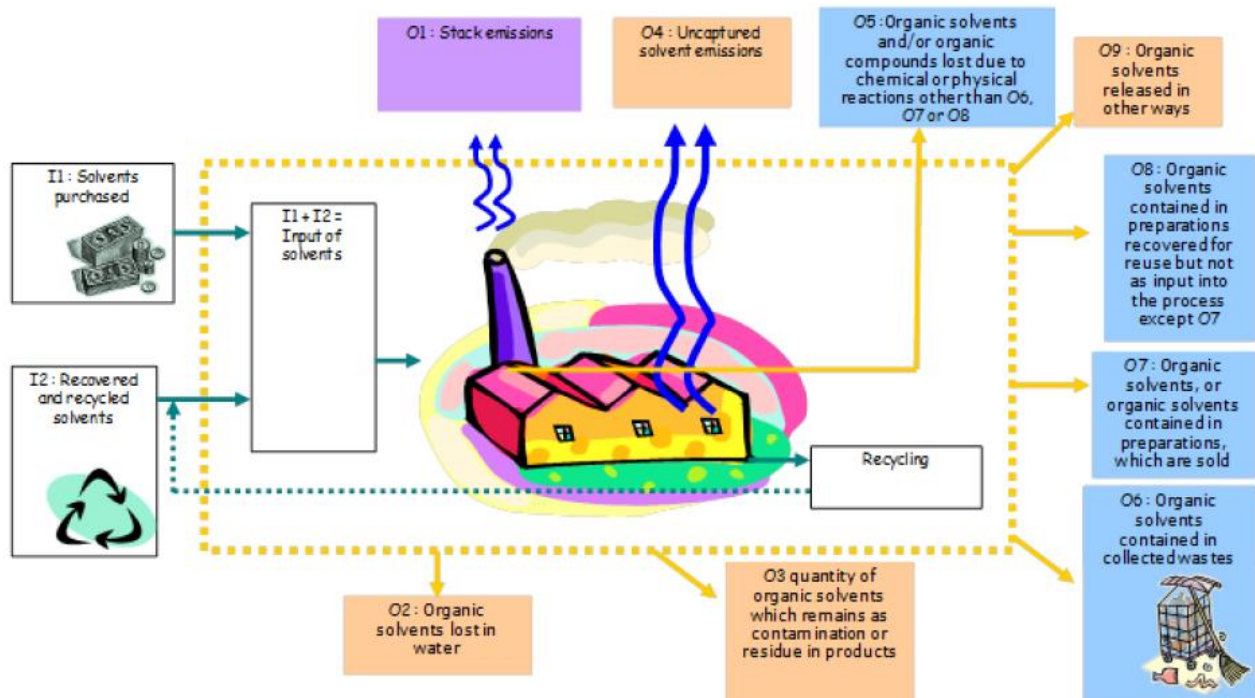
Figure 2: Illustration of the Solvent Mangement Plan

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

Figure 3: The solvent management plan input sheet

Since solvents enter and leave the plant in various manners, the SMP is necessary to determine the amount of emissions to be treated with secondary measures. Furthermore, the amount of fugitive emissions can be calculated. They are directly regulated for certain sectors; therefore, it is important not only to consider the total amount of emissions but also the type of emissions.

In order to determine the solvent input streams, the recovered and recycled solvents (I2) need to be provided by the user. The purchased solvents are then calculated from the total solvent input.

$$m_{I2}\left[\frac{t}{year}\right] = m_{total}^{solvent}\left[\frac{t}{year}\right] - m_{I1}\left[\frac{t}{year}\right] \qquad \text{3-6}$$

Regarding the solvent outputs, the output streams O1, O5, O6, O7 and O8 need to be provided by the user. For the sectors considered in ERICCa_VOC so far, O2, O3, O4 and O9 can be summarized as fugitive emissions. They can be calculated as the difference between the total VOC input and the output streams mentioned above.

$$m_{fugitive}\left[\frac{t}{year}\right] = (m_{total\ input}^{solvent} - m_{O1} - m_{O5} - m_{O6} - m_{O7} - m_{O8})\left[\frac{t}{year}\right]$$ 3-7

The relative shares of the input and output streams are calculated from the absolute numbers by ERICCa_VOC.

Thereof, the emission levels without any measures can be derived. The stack emissions are calculated in 3-8

$$m_{total}^{emissions\ air}\left[\frac{t}{year}\right] = (m_{total\ input}^{solvent} - m_{O5} - m_{O6} - m_{O7} - m_{O8})\left[\frac{t}{year}\right]$$ 3-8

3.3 *Solvent concentration and flow rate*

In order to monitor the compliance with safety regulations, the VOC concentration in the exhaust air is calculated in 3-9, with the annual average flow rate FR_{av} and the operating hours per year OP provided as input parameters by the user. The mass of VOC contributing to the VOC content in the flue gas consists of m_{stack}, the stack emissions provided in O1 of the SMP plus the m_{SM}, the mass of VOC processed through already existing secondary measures (O5 of the SMP).

$$conc_{VOC}\left[\frac{g}{Nm^3}\right] = \frac{\left(m_{stack}\left[\frac{t}{year}\right] + m_{SM}\left[\frac{t}{year}\right]\right) \cdot 10^6 \left[\frac{g}{t}\right]}{FR\ \left[\frac{Nm^3}{h}\right] \cdot OP\ \left[\frac{h}{year}\right]}$$ 3-9

Typical safety regulations require a VOC concentration below 25% of the lower explosion limit (LEL) in the flue gas processed through the plant. Although the LEL varies depending on the actual composition of the solvents in the flue gas, a value of about 1863 kJ/Nm³ [EPA/452/B-02-001] divided by the lower heating value (LHV) of the solvent can be used for estimations.

$$LEL\ \left[\frac{g}{Nm^3}\right] = \frac{1863 \left[\frac{kJ}{Nm^3}\right]}{LHV_{Solvent} \left[\frac{kJ}{g}\right]}$$ 3-10

In order to fulfil the safety regulations, the Flow Rate (FR) needs to be adjusted if the concentration of VOC in the flue gas is higher than 25% of the LEL.

4 Primary Measures

There are different ways to replace products with high solvent contents, in order to lower solvent emissions. In the packaging printing sector, conventional solvent-based products can be replaced by products with a lower solvent content (so-called high-solid or low-solvent products), water-based products, UV-curing inks or two-component adhesives.

In order to calculate the solvent consumption after primary measures, the user has to select which processes to consider for product replacement. The percentage of products to be replaced needs to be provided as well[3]. After providing the total annual solvent content of the replacing products and the mass of solvents needed for cleaning after the replacement, the annual solvent reduction by primary measures is calculated.

$$
\begin{aligned}
m_{solvent}^{after\,PM}&\left[\frac{t}{year}\right] \\
&= \left(100\% - X_{replacement}[\%]\right) \cdot m_{solvents\,in\,r2u\,product}^{initial}\left[\frac{t}{year}\right] \\
&\quad + X_{replacement}[\%] \cdot m_{solvents\,in\,r2u\,product}^{low\,solvent}\left[\frac{t}{year}\right] \\
&\quad + m_{solvents\,for\,cleaning}^{low\,solvent}\left[\frac{t}{year}\right]
\end{aligned}
$$

4-1

4.1 Adaptation of the SMP

In order to consider organizational measures to reduce fugitive emissions, waste or other VOC outputs (e.g. encapsulation of machines or working areas), it is possible to adapt the calculated SMP after primary measures. The total sum of inputs and outputs needs to remain equal because the total amount of solvents in use is usually not affected by organizational measures. The reduction of fugitive or other emissions, however, enables an effective processing of VOC through secondary measures and a controlled release.

4.2 Operating costs

The cost calculation of primary measures is based on user input data. Because of the huge variety of products and processes in different industry sectors, it is impossible to provide generally valid reference data for costs and investments of primary measures. The prices of different products vary, but they are very application specific.

Therefore, the operating costs are determined by the additional costs for the new product (4-2). According to industry information, the use of low-solvent-content inks and products is mainly

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[3] Production lines are usually not operated with a mixture of different types of products. If, however, a plant consists of several lines, it may be the case that not all of them shall be affected by primary measures. In this case, only a certain percentage of products is to be replaced.

motivated by technical and cost considerations, reducing VOC emissions are regarded primarily as a positive side effect. The additional costs ($C_{newproduct,spec}$) might therefore be positive as well as negative and can result in additional costs or benefits.

$$C_{op}\left[\frac{€}{year}\right] = C_{newproduct,spec}\left[\frac{€}{t}\right] \cdot cons_{r2u\ product}\left[\frac{t}{year}\right] \qquad 4\text{-}2$$

The influence of primary measures on other operating costs components, such as utilities or labour is considered very low and therefore not regarded in ERICCa_VOC in order to keep the complexity at a reasonable level.

4.3 Investment

Regarding the investments, the situation is similar. Some plants or lines can easily be converted to other products, whereas others require major investments or completely new machines. Therefore, investment data for primary measures needs to be provided by the user as well. A reference that has been mentioned in older EGTEI documents is displayed in the Reference Box below, which can also be found directly in ERICCa_VOC.

Reference Box - Investment
An average Investment of 25.000 - 190.000 € per varnish or adhesive has been observed. 75.000 € per substituted product or 1.500 € per ton of ready to use product can be used.

4.4 Cost and abatement summary

The total cost of primary measures, the total VOC abatement and thus the specific VOC abatement cost for primary measures are calculated according to chapter 2. A summary with all relevant parameters is displayed in the worksheets 'primary measures' and 'summary' of ERICCa_VOC.

5   Secondary measures

The calculation sheets of the secondary measures (oxidation and adsorption with solvent recovery) can be used in combination with the primary measures worksheet **or separately**. If primary measures are not to be considered, it is also possible to use only the secondary measure calculations. In this case it is not possible to evaluate the adaptations of the SMP (including fugitive emissions) but only the emission reduction in the flue gas will be considered. If the question "Consider primary measures?" in cell C4 is answered with "No", the worksheet "primary" will be ignored and the necessary data has to be inserted directly into the secondary measures sheet (either "Oxidation" or "Adsorption").

The amount of VOC in the exhaust gas that is to be treated with secondary measures is either known from the calculations in the primary measures sheet or provided by the user. Another important parameter is the exhaust gas flow rate, which is used to calculate investment and operating costs. There are two flowrates to be considered, the maximum and the average flow rate. The maximum flow rate is applied for all sorts of design and dimensioning whereas the average flow rate is used for consumption calculations.

The US EPA *Air Pollution Cost Control Manual* [EPA, 2002] is a reference bottom-up approach for emission abatement cost estimations. Oxidiser and adsorber investment calculations in ERICCa_VOC are based on the US EPA approach and adapted with current industry reference data and literature.

5.1   *Oxidation*

Three types of thermal oxidisers are considered in ERICCa_VOC, regenerative, recuperative and recuperative oxidisers with catalyst. The thermal oxidation requires high temperatures that can be reached by natural gas combustion ($T_{combustion}$). Due to the energy content of the solvents, they contribute themselves to the total energy input. Therefore, if the concentration of solvents is high enough, the so-called autothermal point (ATP) can be reached that enables thermal oxidation without further external energy input. The calculation of the ATP is displayed in (5-1) with the density of air ρ_{air}, the specific heat capacity of air $c_{spec,air}$ and the lower heating value of the solvent(s) in use ($LHV_{solvents}$).

$$ATP\left[\frac{g}{Nm^3}\right] = \frac{\rho_{air}\left[\frac{kg}{Nm^3}\right] \cdot (1 - \eta_{ERR}) \cdot (T_{combustion} - T_{fluegas})[K] \cdot c_{spec,air}\left[\frac{kJ}{kgK}\right]}{LHV_{solvents}\left[\frac{kJ}{g}\right]} \qquad \text{5-1}$$

All three types of oxidisers have a reduction efficiency (η_{red}) of about 99%[4]. They differ in their energy recovery rate (η_{ERR}) and their pressure drop (PD). The energy recovery rate (η_{ERR})

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[4] i.e., approximately 99% of the VOCs in the gas stream can be reduced.

describes how much energy (in the form of heat) can be regained from the exhaust gas stream after oxidation to reheat the exhaust gas before oxidation.

Table 3: Reference Values for Oxidiser Types

Reference Box - Oxidiser Type		
	Energy Recovery Rate	Pressure Drop
a) Recuperative oxidators	70 %	3800 Pa
b) Recuperative oxidators with Catalyst	70 %	8000 Pa
c) Regenerative oxidators	95 %	8000 Pa

Regenerative oxidators are commonly applied for an airflow in the range of >1.500 – 70.000 Nm³. For flow rates above 70.000 Nm³ multi-bed systems are used. Above the ATP no pilot flame is required to sustain the oxidation process, resulting in lower gas consumption.

Recuperative oxidators are usually used for small to medium flowrates below 25.000 Nm³ and are most appropriate for continuous processes with a solvent concentration between 6 and 12 g/m³. In contrast to regenerative oxidators, a continuous pilot flame is required to sustain the operation.

A preconcentration system can be considered for high flow rates (between 50.000 and 300.000 Nm³/h) and low concentrations (<500 mg/Nm³). The preconcentration factor f_{precon} is about 10 for flow rates below 70.000 Nm³/h and up to 20 for higher flow rates. The preconcentration results in a higher VOC concentration and lower flow rates. The flow rates after preconcentration are also calculated as average and maximum rates.

$$FR_{av\ or\ max}^{precon}\left[\frac{Nm^3}{h}\right] = \frac{FR_{av\ or\ max}\left[\frac{Nm^3}{h}\right]}{f_{precon}}$$	5-2
$$conc_{VOC}^{precon}\left[\frac{g}{Nm^3}\right] = f_{precon} \cdot conc_{VOC}\left[\frac{g}{Nm^3}\right]$$	5-3

5.1.1 Energy balance

In order to calculate costs and investments of thermal oxidisers, it is necessary to set up an energy balance as basis for the calculation of design and consumption parameters. Energy inputs of thermal oxidisers are the energy content of the VOC, the thermal energy of the flue gas and natural gas combustion. Output streams are primary heat recovery within the oxidiser (for the heating of the flue gas inlet stream), secondary heat recovery for other processes within the plant (if applicable) and losses in the flue gas outlet stream.

The primary energy recovery rate η_{ERR} and the thermal losses of the oxidiser have to be provided by the user as well as the decision whether it is possible to integrate a secondary heat exchanger

and if yes, its efficiency. If a secondary heat exchanger is integrated, the recovered heat can be regarded as benefit reducing the total costs of the installation.

The calculation starts with the energy required to achieve and maintain the combustion temperature $E_{Heat\ demand}$ (5-4) using the average flowrate. If preconcentration is installed, the average flow rate after preconcentration is to be considered. Afterwards, the necessary energy under consideration of the primary energy recovery $E_{Heat\ ER}$ is calculated in (5-5). The energy introduced by the VOC in the fluegas is determined in (5-6).

$$E_{Heat\ demand}\left[\frac{kJ}{year}\right]$$ $$= (\rho_{air}\left[\frac{kg}{Nm^3}\right] \cdot (T_{combustion} - T_{fluegas})[K] \cdot c_{spec,air}\left[\frac{kJ}{kgK}\right] \cdot FR_{av}\left[\frac{Nm^3}{h}\right]$$ $$\cdot OP\left[\frac{h}{year}\right]$$	5-4
$$E_{Heat\ ER}\left[\frac{kJ}{year}\right] = E_{Heat\ total}\left[\frac{kJ}{year}\right] \cdot (1 - \eta_{ERR})$$	5-5
$$E_{VOC}\left[\frac{kJ}{year}\right] = \eta_{red} \cdot LHV_{solvents}\left[\frac{kJ}{g}\right] \cdot conc_{VOC}\left[\frac{g}{Nm^3}\right] \cdot FR_{av}\left[\frac{Nm^3}{h}\right] \cdot OP\ \left[\frac{h}{year}\right]$$	5-6

The heat balance $E_{Heat\ balance}$ is then calculated as the difference between the combustion energy of VOCs and the heat demand considering energy recovery (5-7). If the balance is negative, energy is available for external use (i.e. secondary heat exchanger). If it is positive, natural gas is necessary to produce the required amount of heat. The remaining heat in the exhaust gas is calculated in (5-8) or (5-9). The first equation is valid for operation below the auto thermal point, while the second one is to be used in case of operation above the ATP.

$$E_{Heat\ balance}\left[\frac{kJ}{year}\right] = E_{Heat\ ER}\left[\frac{kJ}{year}\right] - E_{VOC}\left[\frac{kJ}{year}\right]$$	5-7
$$E_{exhaust\ gas}\left[\frac{kWh}{year}\right] = E_{Heat\ demand}\left[\frac{kWh}{year}\right] \cdot (1 - \eta_{ERR} - \eta_{loss})$$ $$if\ conc_{VOC} < ATP$$	5-8
$$E_{exhaust\ gas}\left[\frac{kWh}{year}\right] = E_{Heat\ demand}\left[\frac{kWh}{year}\right] \cdot (1 - \eta_{ERR} - \eta_{loss}) + E_{VOC} - E_{Heat\ ER}$$ $$if\ conc_{VOC} > ATP$$	5-9

5.1.2 Investment

The investment of oxidisers can be derived of the investment curve displayed in Figure 4. This curve was set up by the TFTEI technical secretariat in collaboration with industry representatives. It is based on data from installations of the automotive and packaging printing industry. The curve is validated with several industry experts and has been confirmed as a good estimation for regenerative and recuperative oxidisers. It is also applicable for installations with preconcentration systems, as the additional cost for the preconcentration counterbalances the savings for the smaller design of other components due to the reduced flue gas flowrates.
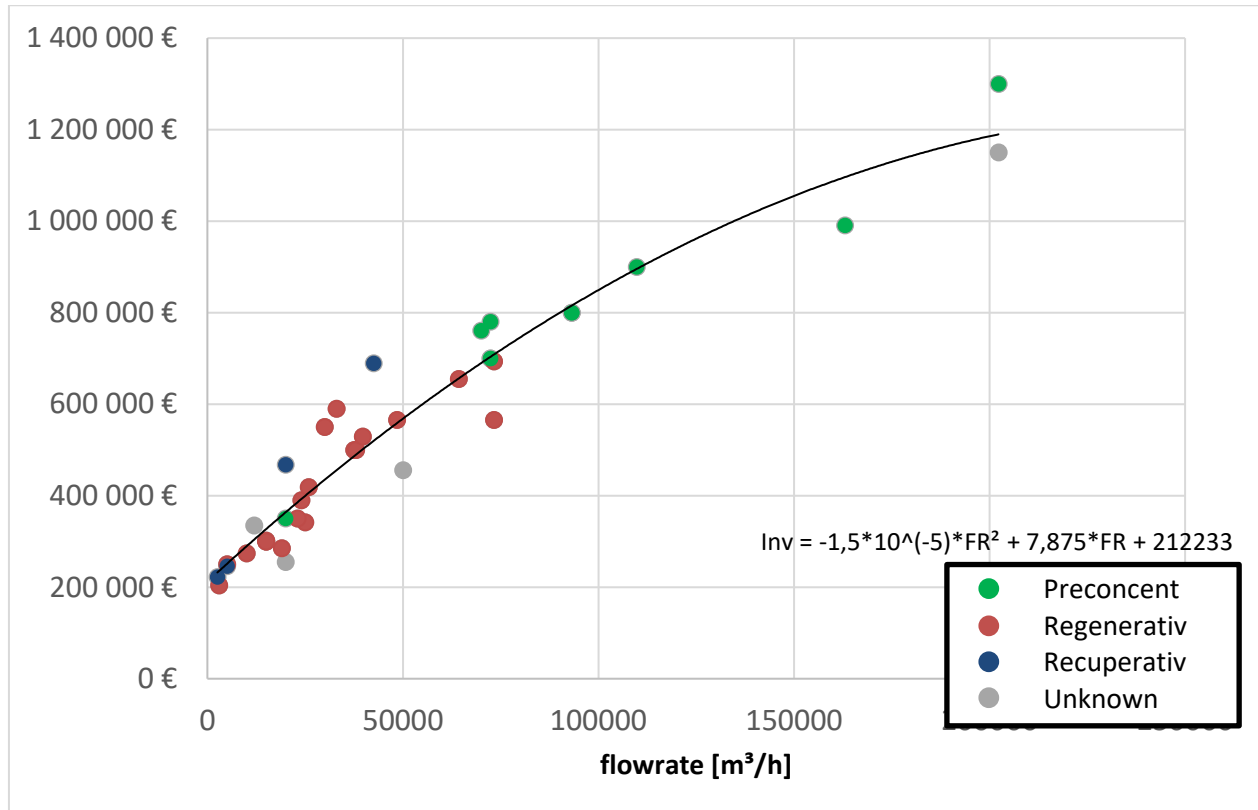

Figure 4: Empirically determined investment curve for oxidisers in [€-2014]

The resulting function for the calculation of the equipment cost is displayed in 5-10. The equation only accounts for the equipment investment. If preconcentration is considered, the initial flow rate needs to be inserted and in any case, the maximum flow rate is to be used, as the system design must be based on maximum conditions. To calculate the total investment (5-11) an additional factor (f_{aux}) accounts for auxiliary installations and other costs. The default value for f_{aux} is 1,85 (cf. [IPCC Guidelines, 2006]).

$Invest_{equip}[€] = -1,5 \cdot 10^{-5} \cdot FR_{max}{}^2 + 7,875 \cdot FR_{max} + 212233)$	5-10
$Invest_{total}[€] = f_{aux} \cdot Invest_{equip}$	5-11

$$Invest_{system}[€] = Invest_{total}[€] + Invest_{2nd\ heat\ exchanger}$$

5-12

If a secondary heat exchanger shall be considered, its investment has to be provided by the user and is added to the total investment sum (5-12). The primary heat exchanger is already included in the original equipment and is thus not added separately.

5.1.3 Variable operating costs

The variable operating costs are caused by the consumption of utilities and the labour required for maintenance.

5.1.3.1 Electricity costs

The electricity consumption (5-13) and the resulting costs (5-14) depend on the fluegas flow rate and the pressure drop of the oxidiser (PD_{oxi}). If a preconcentration is installed the reduced flowrate (FR_{precon}) is to be used and the pressure drop of the preconcentration unit (PD_{precon}) is to be considered additionally. The price of electricity $c_{spec,elec}$ needs to be provided by the user.

$$cons_{elec}\left[\frac{kWh}{year}\right] = \frac{1}{3600000} \cdot FR_{av}\left[\frac{Nm^3}{h}\right] \cdot (PD_{oxi}[Pa] + PD_{precon}[Pa]) \cdot OP\left[\frac{h}{year}\right]$$

5-13

$$C_{elec}\left[\frac{€}{year}\right] = cons_{elec}\left[\frac{kWh}{year}\right] \cdot c_{spec,elec}\left[\frac{€}{kWh}\right]$$

5-14

5.1.3.2 Natural gas costs

The calculation of the natural gas costs is based on the energy balance set up in chapter 5.1.1. Equation (5-15) is valid for positive heat balances due to the resulting need for natural gas in order to maintain the combustion temperature. In case of a negative balance, the energy of the VOC is sufficient, to maintain combustion. Therefore, $E_{Heat\ balance}$ is set to zero for all negative values. Nevertheless, natural gas may be necessary for startup and standby operation, even though the energy in the VOC is on average sufficient. Therefore, the term $E_{startup}$ is introduced. Due to the varying operating schemes of different installations, no reference value can be provided for startup and standby gas consumption, but it needs to be inserted by the user.

$$
\begin{aligned}
C_{naturalgas}&\left[\frac{€}{year}\right] \\
&= \left(E_{Heat\ balance}\left[\frac{kJ}{year}\right] \cdot \frac{1}{3600}\left[\frac{kWh}{kJ}\right] + E_{startup}\left[\frac{kWh}{year}\right]\right) \\
&\quad \cdot c_{naturalgas}\left[\frac{€}{kWh}\right]
\end{aligned}
$$

5-15

5.1.3.3 Costs of labour (maintenance)

The costs of labour are calculated in (5-16). A factor of 6.25% is proposed as a default value for f_{labour} [EPA, 2002], but can be adapted to the user's needs. The specific cost of labour c_{labour} is site specific and needs to be provided by the user

$$C_{labour}\left[\frac{€}{year}\right] = OP\left[\frac{h}{year}\right] \cdot f_{labour} \cdot c_{labour}\left[\frac{€}{h}\right]$$

5-16

5.1.4 Fixed operating costs

The fixed operating costs are calculated as a percentage of the total investment (cf. 5-12). The two major components maintenance and insurance & taxes are considered in ERICCa_VOC.

5.1.4.1 Maintenance costs (without labour)

The annual maintenance costs without labour (as labour was already considered in (5-16) are calculated using the factor for maintenance $f_{maintanance}$. 3% can be regarded as reference value, if no user specific data is available.

$$C_{maintanance}\left[\frac{€}{year}\right] = Invest_{total}[€] \cdot f_{maintanance} \cdot \left[\frac{1}{year}\right]$$

5-17

5.1.4.2 Insurance and taxes

The annual costs of insurance and taxes are calculated accordingly and again, a reference value of 3% of the total investment is considered reasonable.

$$C_{IaT}\left[\frac{€}{year}\right] = Invest_{total}[€] \cdot f_{IaT}[\%] \cdot \left[\frac{1}{year}\right]$$

5-18

5.1.5 Benefits from energy recovery

If the energy balance is negative, excessive heat is available for secondary energy recovery. By installing a secondary heat exchanger, the surplus of energy can be used as process heat within the plant (if there is a constant heat demand within the plant). The efficiency of the secondary heat exchanger η_{2ndER} is considered as well as the price of process heat $b_{processheat}$. The result is $\dot{B}_{processheat}$, the annual benefits generated by secondary heat recovery.

$$\dot{B}_{processheat}\left[\frac{€}{year}\right]$$
$$= -E_{Heat\ balance}\left[\frac{kJ}{year}\right] \cdot \eta_{2ndER}[\%] \cdot b_{processheat}\left[\frac{€}{kWh}\right] \cdot \frac{1}{3600}\left[\frac{kWh}{kJ}\right]$$

5-19

1.1.1 Cross media effects

Greenhouse gases (CO_2, CH_4 and N_2O) and other pollutants (CO and NO_x) are products of the oxidation process. ERICCa_VOC considers those emissions as cross media effects of VOC abatement. Note that NMVOCs converted into CO_2 by the oxidizer are not regarded in the calculations as directly emitted NMVOC (without treatment) are also considered as completely oxidized to CO_2 [IPCC Guidelines 2006]. Therefore, the CO_2 balance is equal with and without VOC abatement.

1.1.1.1 Greenhouse gases

Greenhouse gas emissions (CO_2, CH_4 and N_2O) are based on emission factors (EF_{gas}) of the combustion of natural gas and the natural gas consumption ($E_{NaturalGas}$).

$$emissions_{gas}\left[\frac{kg}{a}\right] = EF_{gas}\left[\frac{kg}{GJ}\right] \cdot E_{NaturalGas}\left[\frac{kWh}{a}\right] \cdot \frac{3,24}{1000}\left[\frac{GJ}{kWh}\right] \qquad \text{5-20}$$

The greenhouse gas emissions are weighted with the global warming potential factor (f_{GWP}) and summed up in order to calculate the greenhouse gas emissions in CO_2 equivalents.

$$emissions_{greenhouse}^{direct}\left[\frac{kg\ eq.CO_2}{a}\right] = \sum_{gas}\left(f_{GWP}\left[\frac{kg\ eq.CO_2}{kg}\right] \cdot emissions_{gas}\left[\frac{kg}{a}\right]\right) \qquad \text{5-21}$$

Besides the direct emissions the indirect emissions from electricity consumption are calculated based on the CO_2 emission factor for electricity generation (EF_{elec}) and the electricity consumption ($cons_{elec}$).

$$emissions_{greenhouse}^{indirect}\left[\frac{kg\ eq.CO_2}{a}\right] = EF_{elec}\left[\frac{g}{kWh}\right] \cdot cons_{elec}\left[\frac{kWh}{year}\right] \cdot 1000\left[\frac{kg}{g}\right] \qquad \text{5-22}$$

The emission factors of the considered pollutants are provided as reference values in ERICCa_VOC.

1.1.1.2 Other pollutants

In order to calculate CO and NOx emissions, the concentration of the pollutant ($conc_{CO}$) in the exhaust gas needs to be provided by the user (these values may differ significantly among different installations). Multiplied with the average flow rate and the operating hours of the oxidiser, the total emissions of the considered pollutant result.

$$emissions_{CO}\left[\frac{kg}{a}\right] = conc_{CO}\left[\frac{mg}{Nm^3}\right] \cdot FR_{av}\left[\frac{Nm^3}{h}\right] \cdot OP\left[\frac{h}{year}\right] \cdot 10^{-6}\left[\frac{kg}{mg}\right] \qquad \text{5-23}$$

$$emissions_{NOx} \left[\frac{eq\ NO_2\ kg}{a}\right] = conc_{NOx} \left[\frac{mg}{Nm^3}\right] \cdot FR_{av} \left[\frac{Nm^3}{h}\right] \cdot OP \ \left[\frac{h}{year}\right] \cdot 10^{-6} \left[\frac{kg}{mg}\right]$$

5-24

1.1.2 Emission summary

The total amount of VOC abated by oxidation can be calculated based on the reduction efficiency of the oxidiser and the amount of stack emissions $m_{solvent}^{stack}$ before the integration of secondary measures.

$$m_{solvent}^{after\ ox} \left[\frac{t}{year}\right] = \eta_{red} \cdot m_{solvent}^{stack} \left[\frac{t}{year}\right]$$

5-25

The total annual costs are calculated as the sum of the annualized investment (cf. chapter 2.1.1) plus the fixed and variable costs. More details regarding the total costs and emission abatement calculation (e.g. with regard to the adaptation of the SMP) will be provided in chapter 6.

5.2 Adsorption with solvent recovery

Adsorption with solvent recovery is a VOC emission reduction technique that is particularly suitable for plants or installations with single solvent use. If several solvents are mixed, it is hardly possible to separate them afterwards. This limitation should be considered when planning an adsorption installation.

The functional principle of adsorbers is the adsorption of VOC to the surface of an adsorbing material, in the given case it is active coal. Thereafter, the VOCs are desorbed from the adsorbing material by steam or hot nitrogen. The desorbed VOCs can be collected and reused within the plant or sold externally. Adsobers are used for flowrates in the range of 1 000 to 1 000 000 m³/h. VOC concentrations between 4 g/Nm³ and 12 g/Nm³ can be considered as common for this application. In general, this technique is about twice as expensive as oxidation [EU 2007]. On the other hand, the recovered solvents can be reused and thus gain a benefit: 'In packaging gravure processes, if ethyl acetate generally makes up over 90 % of the total solvent used, the re-usable amount may be such that the plant becomes almost self-sufficient and no longer needs to buy ethyl acetate for dilution purposes.' [INTERGRAF, 2001]

5.2.1 Adsorber geometry

In order to calculate investment and operating costs of adsorbers, the adsorber geometry needs to be determined first. The calculations in the following are based on [EPA 2002][5].

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[5] [EPA 2002] is available online: http://www.epa.gov/ttn/catc/dir1/c_allchs.pdf (section 3.1, chapter 1).

The number of envisaged desorption (n_{desorb}) and adsorption units (n_{adsorb}) and the adsorption time (T_{adsorb}) need to be provided in the tool and can be used to determine a reasonable maximum desorption time ($T_{desorb,max}$):

$$T_{desorb,max}[h] = T_{adsorb}[h] \cdot \frac{n_{desorb}}{n_{adsorb}}$$	5-26

Adsorption units are alternately operated in adsorption and desorption mode. In adsorption mode, the unit is cleaning the flue gas, adsorbing the VOCs to the activated carbon. In desorption mode nitrogen or steam is used to desorb the VOCs from the carbon and transport them to the solvent recovery unit (cf. Figure 5).
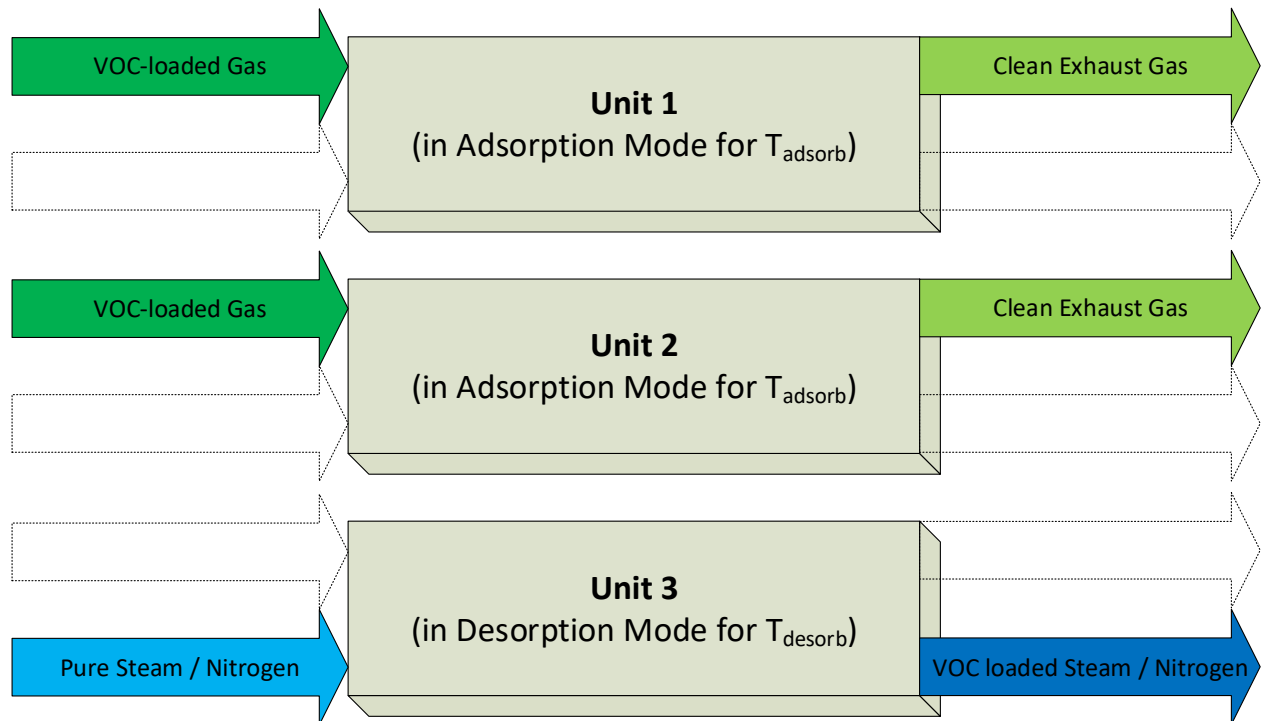

Figure 5: Schematic operating principle of alternating adsorption and desorbtion

Based on the result of (5-26) a reasonable desorption time (T_{desorb}) can be selected by the user. Furthermore, the required amount of active carbon (m_{carbon}) is calculated, based on the adsorption capacity ($Ratio_{VOC,Carbon}$):

$$m_{carbon}[kg] = \frac{m_{inletVOC}\left[\frac{kg_{VOC}}{h}\right] \cdot T_{adsorb}[h]}{Ratio_{VOC,Carbon}[\frac{kg}{kg}]} \cdot (100\% + \frac{n_{desorb}}{n_{adsorb}})$$	5-27

The flowrate per unit ($FR_{max,unit}$) and the amount of carbon ($m_{carbon,unit}$) per unit are calculated as follows:

$$FR_{max,unit}\left[\frac{Nm^3}{h}\right] = \frac{FR_{max}\left[\frac{Nm^3}{h}\right]}{n_{adsorb}}$$

5-28

$$m_{carbon,unit}[kg] = \frac{m_{carbon}[kg]}{n_{desorb} + n_{adsorb}}$$

5-29

Based on this data and the velocity of the gas stream (v_{gas}), the length (L_{unit}), diameter (D_{unit}) and surface (S_{unit}) of the adsorber units are calculated as displayed below:

$$D_{unit}[m] = 0.00787\left[\frac{m^3}{kg}\right] \cdot m_{carbon,unit}[kg] \cdot \frac{v_{gas}\left[\frac{m}{h}\right]}{FR_{max,unit}\left[\frac{Nm^3}{h}\right]}$$

5-30

$$L_{unit}[m] = \frac{125.6\left[\frac{kg}{m^2}\right]}{m_{carbon,unit}[kg]} \cdot \left(\frac{FR_{max,unit}\left[\frac{Nm^3}{h}\right]}{v_{gas}\left[\frac{m}{h}\right]}\right)^2$$

5-31

$$S_{unit}[m^2] = 3,14 * D_{unit}[m] \cdot \left(L_{unit}[m] + \frac{D_{unit}[m]}{2}\right)$$

5-32

The absorber size is limited to practical delimitations (e.g. shipping restrictions). If the size exceeds these limits, additional adsorption und desorption units are to be added.

$$D_{unit}[m] < 4$$

$$L_{unit}[m] < 15$$

5.2.2 Investment

The investment depends primarily on the number of units and the size of the carbon beds as calculated above. [EPA 2002] provides the investment function in (5-33)[6]. Due to the lack of more current data, it was not possible to update this function. However, the accuracy of the results is still assumed acceptable for early stage investment planning.

$$Invest_{perunit}[\text{€}] = \left(271\left[\frac{\text{€}}{m^2}\right] \cdot \left(\frac{Surface[m^2]}{0,0929}\right)^{0.778} \cdot 1,1097\right)$$

5-33

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[6] The original numbers of the EPA document have been converted to metric units and €-2014

A correction factor for the material of the unit (f_{mat}) is then applied in (5-34), based on the reference data in Table 4.

$$Invest_{perunit}^{material}[€] = Invest_{perunit}[€] \cdot f_{mat}$$

5-34

Table 4: Material indeces

Pipe Material Index	f_{mat}
304 Stainless steel	1
316 Stainless steel	1,3
Carpenter 20 CB-3	1,9
Montel-400	2,3
Nickel-200	3,2
Titanium	4,5

The cost of the initial filling with activated carbon ($C_{carbon,init}$) for all units is also part of the investment:

$$C_{carbon,init} = m_{carbon}[kg] \cdot c_{carbon}\left[\frac{€}{kg}\right]$$

5-35

A scale factor (f_{scale}) accounts for economies of scale:

$$f_{scale} = 5.82 \left[\frac{h}{Nm^3}\right] \cdot \frac{FR_{max}[\frac{Nm^3}{h}]}{1.7}^{-0,133}$$

5-36

The equipment investment of all adsorber units ($Invest_{equip}$) is calculated as:

$$Invest_{equip} = ((n_{adsorb} + n_{desorb}) \cdot Invest_{perunit}^{material}[€] + C_{carbon,init}) \cdot f_{scale}$$

5-37

Finally, a factor for additional equipment (f_{equip}) and a factor for auxiliary installations (f_{aux}) is applied to the resulting investment. [EPA 2002] proposes reference values of $f_{equip} = 1,69$ and $f_{aux} = 1,1$. The result of (5-36) is the total investment for the adsorption and solvent recovery installation including auxiliary components.

$$Invest_{total}[€] = (Invest_{adsorber}[€] \cdot f_{aux} \cdot f_{equip})$$

5-38

5.2.3 Variable operating costs

The variable operating costs are determined by the consumption of utilities and the labour required for maintenance. The most relevant components for adsorbing units are listed below.

5.2.3.1 Electricity costs

The electricity consumption and the resulting costs depend on the (average) exhaust gas flowrate and the pressure drop of the adsorber:

$$C_{elec}\left[\frac{€}{year}\right] = \frac{1}{3600000} \cdot FR_{av}\left[\frac{Nm^3}{h}\right] \cdot OP \left[\frac{h}{year}\right] \cdot PD[Pa] \cdot c_{spec,elec}\left[\frac{€}{kWh}\right]$$
5-39

5.2.3.2 Costs of labour (maintenance)

The costs of labour are calculated in 5-40. A factor of 6.25% is proposed as a default value for f_{labour} [EPA, 2002], but can be adapted to the user's needs. The specific cost of labour c_{labour} is site specific and needs to be provided by the user.

$$C_{labour}\left[\frac{€}{year}\right] = OP \left[\frac{h}{year}\right] \cdot f_{labour} \cdot c_{labour}\left[\frac{€}{h}\right]$$
5-40

5.2.3.3 Carbon costs

The carbon in the adsorbers has to be replaced since it loses its adsorption capacity after time. The lifetime of the activated carbon (T_{carbon}) is approximately 5 years [EPA, 2002]:

$$C_{carbon}\left[\frac{€}{year}\right] = \frac{C_{carbon,init}[€]}{T_{carbon}[year]}$$
5-41

5.2.3.4 Costs of vapour/nitrogen

The cost calculation approach for vapour and nitrogen is the same. It is based on the price of either vapour or nitrogen and the amount of vapour/nitrogen that is required to desorb one kg of VOC off the activated carbon ($Ratio_{vapour,VOC}$). The ratio varies among different solvents in a range between 3 and 6 for vapour.

$$C_{vapour}\left[\frac{€}{year}\right] = m_{inletSM}\left[\frac{kg}{year}\right] \cdot Ratio_{vapour,VOC}\left[\frac{kg}{kg}\right] \cdot c_{vapour}\left[\frac{€}{kg}\right]$$
5-42

5.2.4 Fixed operating costs

The fixed operating costs are calculated as a percentage of the total investment (cf. 5-38). The two major components maintenance and insurance & taxes are considered in ERICCa_VOC. Additional components can be added if data is available.

5.2.4.1   Maintenance costs (without labour)

The annual maintenance costs without labour (as labour was already considered in (5-40) are calculated using the factor for maintenance $f_{maintanance}$. 2% can be regarded as reference value, if no user specific data is available.

$$C_{maintanance} \left[\frac{€}{year}\right] = Invest_{total}[€] \cdot f_{maintanance}[\%] \cdot \left[\frac{1}{year}\right] \qquad \text{5-43}$$

5.2.4.2   Insurance and taxes

The annual costs of insurance and taxes are calculated accordingly and a reference value of 3% of the total investment is considered reasonable.

$$C_{IaT} \left[\frac{€}{year}\right] = Invest_{total}[€] \cdot f_{IaT}[\%] \cdot \left[\frac{1}{year}\right] \qquad \text{5-44}$$

5.2.5   Benefits from recovered solvents

The recovered solvents, which can either be reused in the plant or sold externally, gain benefits. The factor for the solvent recovery rate η_{SRR} accounts for the share of solvents that can be recovered. A reference value for the recovery rate is 95%.

$$m_{solvents,recoverd} \left[\frac{kg}{year}\right] = m_{inletSM} \left[\frac{kg}{year}\right] \cdot \eta_{SRR}[\%] \qquad \text{5-45}$$

Recovered solvents can be reused or sold. The share of solvents reused ($Ratio_{reused}$) and sold ($Ratio_{sold}$), the price of solvents replaced by the reused solvents ($c_{spec,reused}$) and the selling price ($c_{spec,sold}$) determine the value of the solvents recovered ($c_{spec,solvents,recovered}$). The total benefits gained by solvent recovery are calculated in (5-47).

$$c_{spec,solvents,recovered} \left[\frac{€}{kg}\right] = Ratio_{sold} \cdot c_{spec,sold} \left[\frac{€}{kg}\right] + Ratio_{reused} \cdot c_{spec,reused} \left[\frac{€}{kg}\right] \qquad \text{5-46}$$

$$B_{solvents,recoverd} \left[\frac{€}{year}\right] = m_{solvents,recoverd} \left[\frac{kg}{year}\right] \cdot c_{spec,solvents,recovered} \left[\frac{€}{kg}\right] \qquad \text{5-47}$$

5.2.6   Emission summary

The total amount of VOC abated by adsorption can be calculated based on the recovery rate of the adsorber and the amount of stack emissions $m_{solvent}^{stack}$ before the integration of secondary measures.

$$m_{solvent}^{after\ ad}\left[\frac{t}{year}\right] = \eta_{SRR} \cdot m_{solvent}^{stack}\left[\frac{t}{year}\right] \qquad\qquad 5\text{-}48$$

The total annual costs are calculated as the sum of the annualized investment (cf. chapter 2.1.1) plus the fixed and variable operating costs. More details regarding the total costs and emission abatement calculation will be provided in chapter 6.

6 Economic summary

For integrated contemplations, ERICCa_VOC provides a summary worksheet with the results of primary and secondary measure calculations. According to the selected secondary measures, the sheet provides results for primary measures in combination with either oxidation or adsorption. It summarizes the solvent in- and outputs, emissions and costs during all stages of the measure, i.e. the initial situation, the results after primary measures and the final results after secondary measures. By selecting the appropriate ELV (emission limit value), the compliance with current regional and sector specific legislation can be checked. Furthermore, the specific abatement costs in [€/t$_{VOC\ abated}$] are calculated in order to evaluate the economic efficiency of different measures. Figure 6 displays the structure of the results as implemented in ERICCa_VOC.

Total

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

Figure 6: Final results of the cost and emission calculation in the summary worksheet

Finally, an analysis of the SMP and its adaptation caused by emission abatement measures is provided. This helps to identify the main solvent processing paths within the plant and the corresponding types of emissions and abatement potentials.

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