TFTEI

TASK FORCE ON TECHNO ECONOMIC ISSUES

VOC Abatement in the coating of passenger cars

TFTEI technical secretariat

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1 Summary

This study has been carried out in order to estimate costs associated with the reduction of VOC emissions from paint shops in the car industry.

To estimate costs of VOC emission reduction, five reference plants have been defined in order to represent all families of paint shops encountered (SB, SB-MIX, WB, integrated process[1]). The reference plants have the same production capacity (a high production) and medium sized bodies are painted.

Three options to reduce VOC emissions for paint shops are considered:

1. Primary measures corresponding to the reduction of VOC emissions at the source (reduction of solvent consumption or improved collection of solvent),
2. Secondary measures to treat waste gases containing VOC (end of pipe techniques),
3. Change for a new paint shop (which enables the use of water based paint systems, advanced paint application systems and waste gas treatment techniques

For each type of measures, parameters followed are estimated:

1. VOC emission reduction potentials based on data coming from plant solvent management plans, modeling and on case studies
2. Annual costs based on case studies and modeling,
3. Cost effectiveness analysis linking VOC emission reduction and annual costs.

To assist the TFTEI technical secretariat to develop the cost estimations for VOC emission reduction from paint shops in the car industry, a working group has been set up with representatives of ACEA and 3 car manufacturers (PSA, Renault, Volkswagen).

The study has been carried out with information provided by the working group. Six meetings with industry experts have been organized to exchange information and discuss the approach set up for cost estimation and results.

Data have been reviewed and agreed with industry.

[1] Families are: SB: entirely solvent-based coating, WB: primer and base coat are water based, SB-MIX: either primer or base coats are solvent based, Integrated process (IP): primerless paint shop with water based base coat.

2 Introduction

This source category covers the coating of cars as part of production and assembly, which are covered by the UNECE definition of M1-vehicles (mainly passenger cars). M1-vehicles are described also in Annex II to the Directive 2007/46/EC establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles [1]: “Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver’s seat.”

VOC emissions from all process stages carried out in the same installation are considered: from electrophoretic coating, or any other kind of coating process, through to the final cavity waxing paint repair activities and polish of topcoating inclusive, as well as solvents used in cleaning of process equipment, including spray booths and other fixed equipment, both during and after the production time.

This document has been prepared with information provided by the European Automobile Manufacturer Association (ACEA). Six meetings have been organized to exchange the information and discuss the approach and results. Data have been reviewed and validated by the industry.

All data and conclusions refer to a reference paint shop line with high production capacity and medium sized body.

Installation:	
Type of vehicle:	passenger car – PC (M1-vehicle)
Body size:	electrophoretic coating area: 97 m² per unit (see chapter 5)
Production capacity:	60 jobs per hour, and 200 000 units per year
Pollutant considered:	VOC
VOC emission:	g/m^2

3 Short technology description

In order to develop this chapter, references [2] were used.

3.1 General description

The automobile body is assembled from a number of welded metal sections. The body and the different parts to be coated, are all processed by the same metal preparation steps.

Surface coating of an automobile body is a multi-step operation carried out on an assembly line conveyor system. Although finishing processes vary from plant to plant, they have some common characteristics.

The different coating steps are as follows (in brackets: common abbreviations):

1. [PT] Pretreatment (cleaning and corrosion protection)
2. [EC] Electrophoretic coating (E-coat (corrosion protection)
3. [SD] Sealing and damping
4. [PR] Primer (smoothing, spreading, stone chip protection, UV protection)
5. [BC] Base coat (colour, colour effects, appearance)
6. [CC] Clear coat (shine, appearance, scratch and chemical resistance)

8. [RE] Finish and paint reworking

7. [CP] Cavity preservation (corrosion protection)

The stages “base coat” and “clear coat” are equivalent of the stage topcoat [TC].

Coatings are either applied by immersion (EC, CP) or by extrusion (SD) or spray processes (SD, PR, BC, CC, FI, CP) of different kinds. Drying/curing occurs in the flash-off areas and bake ovens.

In the car coating, solvents are used at different stages in products such as paints, mastics, diluents and cleaning agents (used for viscosity adjustment, colour change and regular paint line rinses, spray gun or bell cleaning , equipment cleaning, ring pipe flushes).

Within the paint process, VOCs are emitted from the application of electrophoretic coating to the application of clear coat. Small amounts of VOCs are released in the finish / paint repair process and (depending on the material in use in the cavity preservation stage.

3.2 Requirements for quality of paints

The following requirements must be fulfilled by the coatings to meet different specifications:

- protection: resistance against corrosion (humidity), chemicals (insects, cleaning agents), deformations (shocks), impacts (stonce chipping), scratches, sunlight, rapid temperature changes, etc.;
- appearance: impression of deepness in the colour, absence of paint “grains”, brightness, special colour effects.

The primary purpose of electrophoretic coating is to give complete protection against corrosion inside and outside the body.

The filler coat serves not only to improve the appearance (covering the substrate), but also and primarily to give protection against road grit (by elasticity) and to provide an intended rupture point within the filler layer.

The topcoat serves not only to improve appearance (gloss, colour, brilliance), but has also important functions in protecting against chemical and physical environmental influences (sunshine, rain, chemicals, fuels, car-wash plants, and mechanical impact or stress).

3.3 Composition of paints

In order to meet the requirements mentioned above, paints are composed of:

- pigments, to give the colour and opacity to the paint;
- binders, which submit adherence and resistance against mechanical and chemical strain;
- solvents and plasticisers to ease suppleness and applicability;
- additives to improve aspect, paint applicability, conservation, film building, etc.

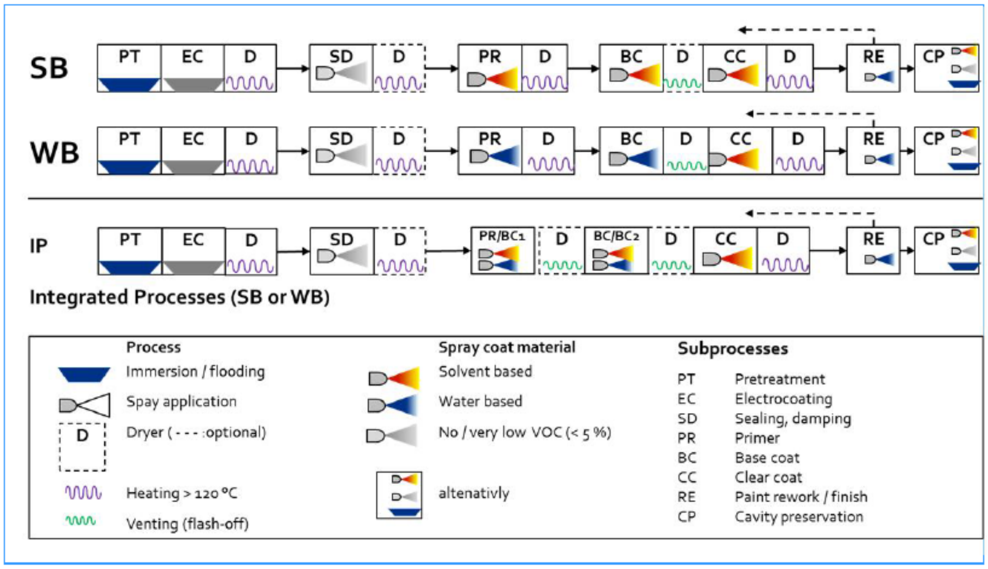
Solvents primarily used in water-based immersion and spray paints are polar substances like ethylene glycol ether, propylene glycol, ethers, their esters, alcohols. Solvent-based paints may additionally contain non polar esters, aromatics, white spirit, ketones and terpenes with poor or no solubility with water.

3.4 Paint shop

With regard to solvent uses and VOC emissions, two basic concepts for spray coating exist: solvent based coatings (SB) and water based coatings (WB). The choice of the coating system entails fundamental and mostly irreversible differences in the design of the paint shop.

Each combination of paint system, associated paint shop design and paint application technique is called a “paint shop family” and each individual paint shop belongs either to the WB or SB paint shop family (figure 1).

Figure 1: WB or SB paint shop families



The technical differences between SB and WB paint shop families exist at several levels:

- spray coating system,
- intermediate dryer between base coat and clear coat,
- dryer oven heating curve,
- construction material for paint booths,
- electrical charging of spray bells,
- spray booth air conditions with regard to temperature, humidity (paint window),
- drying speed.

In existing sites, changing from SB family to WB family can only be done if there is enough room to build a second paint shop (or paint shop line) in parallel without interrupting the existing one. Where these changes are implemented, they are most frequently restricted to only one sub-process (primer or base coat). This type of paint shop is then called SB-MIX paint shop in this study.

In the last 15 years, a new paint shop concept has been developed: integrated process (IP). This paint shop uses a new base coat type which combines the functions of primer and base coat and no longer requires a primer oven. Due to multiple technical constraints, these integrated processes are difficult to install in existing installations.

So, there are 4 families of paint shops which are studied in this report:

- SB: entirely solvent-based coating,
- WB: water-based coats in primer and base coat stage (CC is always clearcoat)
- SB-MIX: either primer or base coats are solvent based ,
- Integrated process (IP): primerless paint shop

The technical lifetime of the basic components (treatment vats, spray booths, dryer ovens…) is up to 40 years, and for application installations (robots, bells, waste gas treatment systems…) between 15 to 20 years.

4 European Union regulation: Industrial Emissions Directive (IED) 2010/75/EU

Annex VII -Technical provisions relating to installations and activities using organic solvents [3]

The ELV_S applies to installations with a solvent consumption larger than 15 t per year.

Emission limits for application of the Directive are presented in the following table.

Additional obligations of the directive are not described in this chapter.

Table 1: Emission limit values (extract of Annex VII – Part 3)

Activity (solvent consumption threshold in tonnes/year)	Production threshold (refers to annual production of coated item)	Total emission limit value	
		New installations	Existing installations
Coating of new cars (> 15)	> 5 000	45 g/m² or 1,3 kg/body + 33 g/m²	60 g/m² or 1,9 kg/body + 41 g/m²
	≤ 5 000 monocoque or > 3 500 chassis-built	90 g/m² or 1,5 kg/body + 70 g/m²	90 g/m² or 1,5 kg/body + 70 g/m²

Emission limit values for installations in the vehicle coating industry:

1. *The total emission limit values are expressed in terms of grams of organic solvent emitted in relation to the surface area of product in m[2] kilograms in relation to the car body[2].*
2. *The surface area of any product dealt with in the table above is defined as the surface area calculated from the total electrophoretic coating area, and the surface area of any parts that might be added in successive phases of the coating process which are coated with the same coatings as those used for the product in question, or the total surface area of the product coated in the installation.*
3. *The surface of the electrophoretic coating area is calculated using the following formula:*

$$\frac{2 \times \text{total weight of product shell}}{\text{average thickness of metal sheet} \times \text{density of metal sheet}}$$

This method shall also be applied for other coated parts made out of sheets.

Computer aided design or other equivalent methods shall be used to calculate the surface area of the other parts added, or the total surface area coated in the installation.

4. *The total emission limit values in the table above refer to all process stages carried out at the same installation from electrophoretic coating, or any other kind of coating process, through to the final wax and polish of topcoating inclusive, as well as solvent used in cleaning of process equipment, including spray booths and other fixed equipment, both during and outside of production time.*

[2] Usually only the first alterative is used for stipulating emission limit values in environmental permits. Accordingly, in this paper VOC emissions are expressed in g/m² only.

5. *Vehicle coating installations below the solvent consumption thresholds mentioned in the above table shall meet the requirements for the vehicle refinishing sector.*

For IED installations with a solvent consumption capacity of more than 150-kg per hour or more than 200 tons per year (part 6.3 of Annex I), article 15 (Emission limit values, equivalent parameters and technical measures) also applies:

The competent authority shall set emission limit values that ensure that, under normal operating conditions, emissions do not exceed the emission levels associated with the best available techniques as laid down in the decisions on BAT conclusions referred to in Article 13(5) through either of the following:

(a) setting emission limit values that do not exceed the emission levels associated with the best available techniques. Those emission limit values shall be expressed for the same or shorter periods of time and under the same reference conditions as those emission levels associated with the best available techniques; or

(b) setting different emission limit values than those referred to under point (a) in terms of values, periods of time and reference conditions.

Where point (b) is applied, the competent authority shall, at least annually, assess the results of emission monitoring in order to ensure that emissions under normal operating conditions have not exceeded the emission levels associated with the best available techniques.

5 Definition of reference installations

Five reference plants have been defined in order to represent all families of paint shops (SB, SB-MIX, WB, integrated process[3]).

These five reference plants have in common the following parameters:

- Annual production: 200 000 car bodies per year (passenger cars only), corresponding to 2x8 shift works loaded (60 jobs per hour)
- Electrophoretic coating area: 97 m^2/car

The stages pre-treatment, e-coat, sealing-damping, reworking and cavity preservation are common to all reference plants.

The stages which are different, correspond to the primer, the base coat and the clear coat as presented in the table below.

In table 2, existing 74 individual passenger car paint shops were assigned to one of the paint shop family [4]. There are only four paint shops that use paint concepts that are not covered in this study.

Table 2: Definition of reference plants

Paint shop family:	**1** ***SB***	**2A** ***SB-MIX***	**2B** ***SB-MIX***	**3** ***WB***	**4** ***Integrated process***
Pretreatment	X	X	X	X	X
E-coat	X	X	X	X	X
Sealing and damping	X	X	X	X	X
Primer	**SB**	**WB**	**SB**	**WB**	**-**
Base coat	**SB**	**SB**	**WB**	**WB**	**WB**
Clear coat	**SB**	**SB**	**SB**	**SB**	**SB**
Cavity preservation	X	X	X	X	X
Paint reworking	X	X	X	X	X
Number of installations in the EU (in 2014)	6	20		32	12

SB = solvent-based coating/ WB = water-based coating

In the following chapters the paint shop families “2A” and “2B” are not discussed separately as (a) only a few paint shop data are available for each family and (b) the reported figures suggest that the key input and output parameters are very similar in both groups and do not justify a clustering in different groups.

3 Families are: SB: entirely solvent-based coating, WB: primer and base coat are water based, SB-MIX: either primer or base coats are solvent based, Integrated process (IP): primerless paint shop with water based base coat.

6 Empirical data for solvent inputs and outputs for the reference plants

Solvent inputs and outputs for reference plants are based on data on Solvent Management Plans (SMP) provided by 18 plants in Europe (2014) [5]. VOC emissions and types of air treatment used are based on data from 60 plants in Europe (2012-2013-2014) [4] provided by ACEA.

According to IED directive, the SMP shall be used to:

(a) verify compliance as specified in Article 62;
(b) identify future reduction options;
(c) enable provision of information on solvent consumption, solvent emissions and compliance with the requirements of Chapter V to the public.

SMP is a mass balance providing data about inputs and outputs of solvents within the installation. In the case of car industry, a simplified solvent management plan can be carried out because only total ELVs are implemented (expressed in g VOC/m^2). Mass balances usually cover one calendar year.

The SMP is a key instrument to understand VOC sources and take decisions in terms of VOC emissions reduction.

For passenger car paint shops, solvent balances are usually calculated using the following solvent input and output mass flows:

- I1 the quantity of organic solvents or their quantity in preparations purchased which are used as input into the process in the time frame over which the mass balance is being calculated.
- O5 organic solvents and/or organic compounds lost due to chemical or physical reactions (including for example those which are destroyed, e.g. by oxidation or other waste gas or waste water treatments, or captured, e.g. by adsorption, as long as they are not counted under O6, O7 or O8).
- O6 organic solvents contained in collected wastes.
- O8 organic solvents contained in preparations recovered for reuse but not as input into the process.

Total VOC emissions are defined as follows:

Total VOC emissions = I1 – O5 – O6 – O8 ***Eq. 1***

Solvent inputs and outputs for the reference installations are presented in the following table, expressed as g VOC per m^2 e-coat surface. The first line shows average values for the respective paint shop family and process step. The figures in the second line describe minimum and maximum values reported in the above-mentioned data survey.

The details of inputs and outputs are based on 18 SMP [5] and VOC emissions are based on ACEA statistics [4]. This large number of plants used enable to consolidate the representativeness of VOC emissions for each reference installation.

Table 3: solvent inputs (I1) and outputs (O5, O6, O8) of reference plants

		1 ***SB***	**2** ***SB-MIX***	**3** ***WB***	**4** ***Integrated process***	***Reference***
I1 step by step (g/m^2)	E-coat	2.1 [0.7 – 6.5]	2.1 [0.7 – 6.5]	2.1 [0.7 – 6.5]	2,1 [0,7 – 6,5]	[5]
	Sealing Damping	5.0 [0.0 – 7.8]	5.0 [0.0 – 7.8]	5.0 [0.0 – 7.8]	5,0 [0,0 – 7,8]	[5]
	Primer	6.1 [4.6 – 7.0]	3.5 [1.4 – 7.0]	2.0 [1.4 – 2.7]	0,0 [0,0 – 0,0]	[5]
	Base coat	20.6 [17.1 – 26.2]	14.4 [6.0 – 19.3]	4.9 [2.7 – 6.1]	5,9 [4,5 – 8,5]	[5]
	Clear coat	12.4 [8.8 – 18.8]	11.3 [10.0 – 12.0]	11.2 [8.3 – 14.1]	8,8 [6,7 – 12,0]	[5]
	Cavity preservation	0.4 [0.0 – 1.6]	0.4 [0.0 – 1.6]	0.4 [0.0 – 1.6]	0,4 [0,0 – 1,6]	[5]
	Cleaning and other minor applications	29.9 [17.0 – 54.2]	15.0 [10.0 – 18.0]	10.0 [6.4 - 14.9]	7,3 [1,4 – 15,7]	[5]
I1 Total (g/m^2): Quantity of organic solvents used as input into the process		78,3 [62,0 – 114,5]	51.2 [43.0 – 57.0]	35.7 [26.9 – 45.7]	26.9 [18.3 – 34.8]	[5]
O6/O8 (g/m^2) Quantity of solvents contained in collected wastes and in preparations recovered for reuse		19,1 [15,0 – 24,1]	12.5 [8.0 – 16.6]	3.1 [1.3 – 6.0]	3.4 [0.4 – 6.8]	[5]
O5 (g/m^2) Quantity of organic solvents destroyed by oxidation		12,3 [9,0 – 19,2]	5.8 [1.5 – 8.0]	9.7 [6.1 – 15.3]	7.1 [4.1 – 12.5]	[5]
VOC EMISSION (g/m^2) Average [Min – Max]		**37,8** [16,8 - 50,3]	**28.7** [12.5 - 48.2]	**18.6** [6.0 - 30.5]	**20.5** [8.9 - 32.1]	[4]

[5] 18 Solvent Management Plans (SMP) from car industries in Europe (2014)
[4] Statistics from ACEA (average for 2012, 2013, 2014) – 60 plants in Europe

The range of values within each group (paint shop family) can be explained by several causes:

- the variability of techniques used:
  - the application techniques and their associated paint transfer efficiency (primary measure),
  - the collection of solvent (primary measure),
  - the optimisation of cleaning (primary measure),
  - the implementation of air treatment for the oven/dryers (secondary measure),
  - the implementation of air treatment for the spray booths (secondary measure).

- the variability of products used:
  - the relation between electrophoretic surface and painted surface, causing different paint consumptions for bodies with comparable size (e-coat area)
  - the quality of coating and fashion: for example the construction of two-tone cars (after the body has been completely coated with one colour, part of the surface is masked and the

body is reintroduced in the base coat line to apply the second colour. This results in additional VOC emissions).

An assessment of individual SMP presented in table 3 shows, that most solvents are used for spray coating in the primer, basecoat and clearcoat cabins. The table 4 presents the ratios of the sum of solvent inputs to spray application and diluting/cleaning for spray application on total input I1.

Table 4: Percentage of solvents inputs for spray application relative to the entire paint shop

	1 ***SB***	**2** ***SB-MIX***	**3** ***WB***	**4** ***Integrated process***	***Reference***
I1 total input (g/m^2)	78.3 [62.0 – 114.5]	51.2 [43.0 – 57.0]	35.7 [26.9 – 45.7]	26.9 [18.3 – 34.8]	[5]
I1 for spray application (primer, base coat and clear coat) and cleaning/dilution (g/m^2)	69.1 [54.0 – 100.2]	44.2 [35.0 – 49.0]	28.1 [19.7 – 37.8]	22.0 [13.3 – 33.6]	[5]
Ratio (calculated from the averages)	88 %	86 %	79 %	82 %	

[5] 18 Solvent Management Plans (SMP) from car industries in Europe (2014)

7 VOC abatement techniques and their efficiency

Three options to reduce VOC emissions are considered in this study:

1. Primary measures corresponding to the reduction of VOC emissions at the source (reduction of solvent consumption or improved collection of solvent),

2. Secondary measures to treat waste gases containing VOC (end of pipe techniques),

3. Change for a new paint shop (which allows to employ water based paint systems and advanced paint application and waste gas treatment techniques).

Time necessary for implementation of the various abatement techniques in existing plants is presented in the table 5.

Table 5: Time required for implementation of VOC abatement techniques

VOC abatement by:	Time required for planning and implementation
Primary measure	Several months – less one year
Secondary measure	Roughly one year
New paint shop	Three to five years

7.1 Primary measures

Possible primary measures are as follows:

- Improved solvent management (for example collection of solvent),
- Optimisation of cleaning cycles,
- Improvement of transfer efficiency and application technology.

Various single techniques can be used in different or all steps of the coating process and usually a combination of techniques are used.

In order to evaluate the emissions reduction potential of possible primary measures, data were collected from some 22 plants in Europe [6]. The summary of these data is presented in table 6. These primary measures correspond to the main techniques implemented in car industries, based on real life cases and applied in paint shops of different families; however this list is not exhaustive.

Table 6: VOC emission reduction - primary measures (case studies)

Primary measures	***Reduction of VOC emission (g/m^2)***	***Number of sites for data collection***	***Reference***
Collection of solvents	2.4 [0.5 – 4.5]	5	[6]
Optimisation of cleaning cycles	0.6 [0.05 – 1.8]	6	[6]
100% automation of primer, base coat, clear coat	1.2 [1.1 – 1.2]	2	[6]
Optimisation of colour change technology (base coat)	0.5 [0.07 – 1.1]	4	[6]
Innovative application technology (e.g bell-bell)	0.8 [0.6 – 1]	2	[6]
100% Automation of interior coating, with rotational bell atomisation and low loss colour changers (base coat, clear coat)	2.6 [0.8 – 6]	2	[6]
Replacement of pneumatic guns application with robots by electrostatic bells (base coat)	0.23	1	[6]

[6] Data collection from 22 plants in Europe

An examination of these examples shows that it is not possible to deduct the maximum achievable VOC emission reduction by summing up all possible different primary measures for two reasons:

1. The specific emissions reduction effect of each single measure is different for each process step and used paint system. Moreover, it was not possible to collect enough operational data to cover all cases,

2. Not all primary measures can be combined, some measures are mutually exclusive.

In order to estimate a potential of VOC emission reduction with primary measures, a statistical approach based on the assessment of SMP from 18 passenger car paint shops is realised.

Firstly, VOC emissions for each SMP of the different reference installations without implementation of secondary measures (O5 in the individual SMP are set to “0”) are estimated with the following formula:

$$\textbf{VOC emission}_{\text{(without secondary measure)}} = \textbf{I1 – O6 – O8} \qquad \textbf{Eq. 2}$$

Equation 2 expresses in a general way, the effect of primary (process integrated) measures on solvent consumption I1 (by optimizing coating efficiencies) or waste collection (O6) and reuse of solvents (O8).

Secondly, the potential of VOC emission reduction is estimated based on the range between the maximum and minimum value for the total VOC emissions among SMP. To take into account that product related issues have an additional large impact on solvent consumption (I1) in a given paint shop (see chapter 6), experts from car industry suggested to assign 50 % of this span to maximum effect of primary measures and 50% as product related.

The potential of VOC emission reduction by primary measures is calculated for each reference installation with the following formula:

$$\textbf{Potential of VOC emission reduction = [Maximum (I1-O6-O8) – Minimum (I1-O6-O8)] * 50\%} \qquad \textbf{Eq. 3}$$

It should be noted that the potential of VOC emission reduction can't be recalculated directly without the details of SMP (confidential). These estimations are based on data for each SMP and not on the averages presented in table 3, in order to be closer to the exact data.

Table 7: Potential of VOC emission reduction - primary measures (SMP)

Reference Installations	1 *SB*	2 *SB-MIX*	3 *WB*	4 *Integrated process*	*Reference*
VOC emission (g/m^2) without secondary measure (air treatment) (I1 – O6 – O8)	59.3 [42.9 – 95.2]	38.7 [35.0 – 44.0]	32.5 [25.0 – 42.3]	23.5 [17.9 – 31.9]	[5]
Potential of VOC emission reduction (g/m^2) 50% * (Maximum value – Minimum value)	26.2	4.5	8.7	7.0	[5]

[5] 18 Solvent Management Plans (SMP) from car industries in Europe (2014)

7.2 Secondary measures

In this study, two techniques are considered as secondary measures in paint shops:

- Oxidation of VOCs in waste gases from ovens and/or spray booths without pretreatment with concentrating of VOC,
- Zeolite adsorption (concentration step) followed by thermal oxidation.

The zeolite adsorber acts as a concentrator of the large raw gas volume with low VOC concentration into a much smaller and highly concentrated air flow which is then sent to the thermal oxidizer. The advantage of this system is to enable an oxidation of VOC in a smaller oxidiser under or close to autothermal combustion conditions.

To estimate the reduction in total VOC emissions related to the implementation of a waste gas treatment, data from the SMP of existing installations could be assessed. Indeed, quantities of solvents destroyed (O5) are indicated in SMP and could be assigned to the type of treatment. VOC emission reductions obtained with the implementation of an air treatment on the dryers / ovens and the spray booths can therefore be deduced from the SMP provided.

The potential of VOC emissions reduction is based on the quantity O5 in SMP provided. Two cases are considered:

- with air treatment on the dryers/ovens only,
- with air treatment on the dryers/ovens and spray booths.

With SMP data [5] alone, all possible combinations are not covered. For a given type of installation or step, when there is no O5 associated, the ACEA statistics [4] are used to derive O5 according to the characteristics of the plants.

It should be noted that the potential of VOC emission reduction can't be recalculated directly without the details of SMP and ACEA statistics (confidential). These estimations are based on data for each SMP and not on the averages presented on the table 3, in order to be closer to the actual data.

Table 8: Potential of VOC emission reduction - secondary measures (SMP)

Reference Installations	**1** *SB*	**2** *SB-MIX*	**3** *WB*	**4** *Integrated process*	***Reference***
VOC emission (g/m^2) without air treatment (I1-O6-O8)	59.3 [42.9 – 95.2]	38.7 [35.0 – 44.0]	32.5 [25.0 – 42.3]	23.5 [17.9– 31.9]	[5]
Potential VOC emission reduction with implementation of air treatment on ovens/dryers (g/m^2) O5 air treatment on dryers/ovens	11.2 [9.0 – 16.6]	5.8 [1.5 – 8.0]	9.7 [6.1 – 15.3]	7.1 [4.1 – 12.5]	[5]
VOC emission with air treatment (ovens/dryers) (g/m^2) (I1-O5-O6-O8)	55.3 [38.0 – 78.6]	32.9 [27.0 – 36.0]	22.8 [18.9 – 28.5]	16.4 [13.0 – 25.3]	[5]
Potential VOC emission reduction with implementation of air treatment on ovens/dryers and spray booths (g/m^2) O5 air treatment on dryers/ovens and spray booths	14.6 [10.0 – 19.2]	14.0	11.6	1.5	[5] [4]
VOC emission with air treatment (ovens/dryers + spray booths) (g/m^2) (I1-O5-O6-O8)	30.3 [23.7 – 37.0]	17.0 [12.5 – 23.5]	8.8 [6.0 – 11.8]	19.3 [12.4 – 26.1]	[5] [4]

[5] 18 Solvent Management Plans (SMP) from car industries in Europe (2014)

[4] Statistics from ACEA (average for 2012, 2013, 2014) – 60 plants in Europe

The data taken into account for the estimation of potential VOC reduction (table 8) allow to know only if at least one of the dryers/ovens is treated and at least a spray booth is treated. Potentials of VOC reduction on the table 8 do not represent the maximum potential of VOC emission reduction but the difference in term of VOC emissions between plants without any treatment on dryers/ovens or spray booth and plants with at least one oxidizer to these places.

The tool ERICCa_VOC [7], developed in the scope of this project, is able to estimate the costs (investments, fixed and variable operating costs and total annual costs) associated with different reduction techniques such as thermal oxidizer (secondary measure). ERICCa_VOC is used to estimate the VOC emission reduction and costs associated with the implementation of secondary measures.

Input data requested to run the tool are presented in table 9 and the results of the modeling for VOC emission reductions in the table 10. Only the main steps contributing to VOC emissions are simulated: primer, base coat and clear coat.

Representative VOC concentrations and flow rates are estimated using average emission factors from submitted SMP and information from car industry experts. Each case simulated with the tool corresponds to regenerative oxidizer. Pre-concentration is applied when it is feasible[4] (air flow rate > 50 000 Nm^3/h and

[4] In the tool ERICCa_VOC, the user is informed automatically if the pre-concentration option is favourable.

VOC concentration < 500 mg/Nm^3).The complete diagrams of VOC flow distribution are presented for each reference installation in Annex 1.

The simulations carried out with ERICCa_VOC represent typical examples on paint shop and present average values. However they don't take into account all possible cases (ERICCa_VOC can be used for any specific context on a plant).

Table 9: Input data for modeling with ERICCa_VOC

		Air flow rate (Nm^3/h)	VOC concentration (mg VOC/Nm^3)				
			1 *SB*	2A *SB MIX*	2B *SB MIX*	3 *WB*	4 *Integrated Process*
Primer	Spray booth	200 000	171	41	167	58	-
Primer	Dryer	30 000	440	106	429	150	-
Base coat	Spray booth including flash off/ intermediate dryer	200 000	573	450	143	147	164
Clear coat	Spray booth	200 000	514	394	351	409	315
Clear coat	Dryer	30 000	878	672	600	699	538

VOC emission reductions are estimated with ERICCa_VOC (input data presented in table 9). An efficiency of 99 % for the oxidizer is considered for all the cases, based on supplier data.

In table 10, maximum reduction of VOC emission is estimated by modeling the processing on all the dryers/ovens and spray booths.

Table 10: VOC emission reductions - secondary measures (modeling)

		Reduction of VOC emission (g/m^2)					Reference
		1 *SB*	2A *SB MIX*	2B *SB MIX*	3 *WB*	4 *Integrated Process*	
Primer	Spray booth	5.8	1.4	5.7	2.0	-	[6]
	Dryer	2.2	0.5	2.2	0.8	-	[6]
Base coat	Spray booth including flash off/ intermediate dryer	19.5	15.3	4.9	5.0	5,6	[6]
Clear coat	Spray booth	17.5	13.4	11.9	13.9	10,7	[6]
	Dryer	4.5	3.4	3.1	3.6	2,7	[6]
Maximum reduction of VOC emission estimated (sum)		49,5	34.1	27.7	25.2	19.0	

[6] ERICCa_VOC

7.3 New paint shop

Due to several differences in paint shop design (see part 2.4), a change from solvent-based to water-based spray coats cannot be made without radical modification of the paint shop characteristics and often requires to build a new paint shop.

In existing sites, a change from a SB family paint shop to a WB family one can only be done if there is enough place to build a second paint shop (or paint shop line) in parallel to the existing one without interrupting it. Where these changes are implemented, they are most frequently restricted to only one sub-process (primer or base coat, SB → SB-MIX).

Among other decisions to be made in planning a new paint shop, the following choices influence the level of VOC emissions from paint shop:

1. coating concept (paint shop family),
2. level of primary measures (paint application, colour change and cleaning systems and procedures,
3. extent of secondary measures (waste gas treatment of dryer oven and spray cabin waste gas)

In this chapter, the consequences of these decisions are described for a hypothetical new paint shop using data from available SMP already presented in table 3.

With regard to paint concepts, the most relevant differences are between paint shop family 1 / 2 as compared to 3 / 4. Only these are taken into account in this study.

As already explained, VOC emissions without implementation of secondary measure (O5 in SMP) are firstly estimated with the equation 2 (Eq. 2) (see table 7).

Secondly, the potential of VOC emission reduction is based on the difference between the average value of the reference installation before and after the change of paint shop. The results are presented in table 11.

For example, to estimate the potential of VOC reduction between 1 (SB) and 3 (WB), the averages of VOC emissions without secondary measure (table 7) for both types of paint shop are considered:
59,3 – 32,5 = 26,8 g/m^2

Table 11: Potential of VOC emission reduction - new paint shops (SMP)

Comparison between:	**Potential of VOC reduction emission (g/m^2)**	**Reference**
1 (SB) and 3 (WB) *water based primer and basecoat instead of solvent based systems*	26.8	[5]
1 (SB) and 4 (Integrated process) *solvent based primer and base coat versus water based IP base coat*	35.8	[5]
2 (SB-MIX) and 3 (WB) *water based primer and base coat instead of solvent baseds coats in one of these steps*	6.2	[5]
2 (SB-MIX) and 4 (Integrated process) *water based IP base coat instead of separate primer and base coat, where one of these coats is solvent based.*	15.2	[5]

[5] 18 Solvent Management Plans (SMP) from car industries in Europe (2014)

In order to define possible changes for a new paint shop and associated VOC emission reduction based on real life cases, data were collected from some 13 plants (9 in Europe and 4 outside Europe) [8]. On 13 plants, 6 correspond to a modification of the paint shop and 7 to the construction of a new paint shop. Data on reduction of VOC emissions are available for four plants of six. The summary of these data is presented in the table 12.

Table 12: VOC emission reductions - new paint shops (case studies)

Change for a new paint shop	Reduction of VOC emission (g/m^2)	Amount of sites for data collection	Reference
1 (SB) to 3 (WB) *Switching the primer and the base coat from solvent-based to water-based coating*	41.0	1	[8]
1 (SB) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating and remove the primer*	27 [25 – 28]	2	[8]
2 (SB-MIX) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating or remove the primer*	15.0	1	[8]

[8] Data collection from 13 plants in Europe and outside Europe

Comparison between tables 11 (SMP) and 12 (case studies) shows that individual paint shops data can be different from estimated average data.

Nevertheless data from table 11 can be used for forecasting the overall long term effect of changing the number of installations in the different paint shop families due to major refurbishments of existing installations or building of completely new greenfield paint shops.

8 Cost calculation

8.1 Composition of costs

In the assessment process of BATs, the total annual costs, C_{tot}, as well as the specific annual costs for abating the pollutant *i* are essential. They are defined according to equations 4 and 5.

$$\mathbf{C_{tot}}\left[\frac{€}{\mathbf{year}}\right] = \mathbf{C_{cap}}\left[\frac{€}{\mathbf{year}}\right] + \mathbf{C_{op}}\left[\frac{€}{\mathbf{year}}\right]$$	**Eq. 4**
$$\mathbf{C_{tot,spec,i.}}\left[\frac{€}{\mathbf{mass}}\right] = \left(\mathbf{C_{tot}}\left[\frac{€}{\mathbf{year}}\right]\right) \cdot \left(\mathbf{m_{i,year}}\right)^{-1}\left[\frac{\mathbf{year}}{\mathbf{mass\ abated}}\right]$$	**Eq. 5**

The total specific abatement cost per mass of pollutant *i*, $C_{tot,spec,i}$ is calculated by dividing the total annual cost in Euro by mass of abated pollutant $m_{i,year}$, usually metric tons or kilograms per year. Total operating costs, C_{op}, are composed of fixed and variable operating costs. C_{cap} is annualised capital cost.

The specific total annual costs are presented in detail in the following chapters.

8.1.1 Investment

Investments should include three components [9]:

- Pollution control equipment expenditure,
- Installation expenditure,
- Contingency provisions.

Literature data on investments very rarely give details on the components taken into account, so that comparisons are difficult. Investments for pollution control equipment and installation expenditure including permits, insurance, contingency etc. are usually given without taxes. To calculate the investment for an existing installation, a retrofit factor *r* is used and represents the additional costs compared to an installation of the same equipment at a new plant.

For calculating costs of air pollution equipment in an annual level, the costs of the initial investment need to be spread onto each year of operation. The annualised capital cost C_{cap} can be calculated according to equation 6 with the parameters *p* (interest rate) and *n* (equipment technical or economic lifetime) and investment cost C_{inv}.

$$\mathbf{C_{cap}} = \mathbf{C_{inv}} \cdot \frac{(\mathbf{1}+\mathbf{p})^{\mathbf{n}}}{(\mathbf{1}+\mathbf{p})^{\mathbf{n}}-\mathbf{1}} \cdot \mathbf{p}$$	**Eq. 6**

8.1.2 Operating Costs

Total operating costs, C_{op}, are composed of fixed and variable operating costs.

$$\mathbf{C_{op}}\left[\frac{€}{\mathbf{year}}\right] = \mathbf{C_{op,fix}}\left[\frac{€}{\mathbf{year}}\right] + \mathbf{C_{op,var}}\left[\frac{€}{\mathbf{year}}\right]$$	**Eq. 7**

The fixed operating costs, $C_{op,fix}$ are usually calculated as a percentage of the unit investment and include costs such as maintenance, insurance, wages, etc. Variable operating costs $C_{op,var}$ include costs for utilities such as electricity, natural gas, waste disposal, consumables, etc. (C^{unit}).

$$\mathbf{C_{op,var}}\left[\frac{€}{\mathbf{year}}\right] = \sum \mathbf{C^{unit}}\left[\frac{€}{\mathbf{year}}\right], \mathbf{unit} \in \{\mathbf{equipment, consumables, electricity, disposal}\}$$	**Eq. 8**

8.2 Costs of primary measures

The estimated costs of primary measures are based on data provided by car manufacturers who set up this type of reduction measures. In order to define investment costs on the paint shop and VOC reduction associated, data were collected from some 22 plants in Europe. The summary of these data is presented in table 13.

The operating costs or profits of primary measures are difficult to estimate by car industries. Therefore only investment costs are considered (building and equipment).

Table 13: Investment costs - primary measures

Primary measures	**Investment cost**	**Number of sites considered for data collection**	**Technical capacity of the paint shop segment**	**References**
	millions €			
Collecting solvents	0.3 [0.2 – 0.5]	5	30 - 60 jobs per hours (jph)	[6]
Optimizing cleaning cycles	0.0002 [0 – 0.0007]	6	30 - 60 jph	[6]
100% automation of primer, base coat, clear coat	10 [3 - 16]	2	30 - 60 jph	[6]
Optimizing colour change technology (base coat)	1 [0.6 - 1.3]	4	30 - 60 jph	[6]
Innovative application technology (e.g. bell-bell)	0.9 [0.7 – 1]	2	30 - 60 jph	[6]
100% Automation of interior coating, with rotational bell atomisation and low loss colour changers (base coat, clear coat)	15.7 [8.1 – 25.2]	2	estimated for 60 jph	[6]
Replacement of pneumatic guns application with robots by electrostatic bells (base coat)	0.71	1	estimated for 60 jph	[6]

[6] Data collection from 22 plants in Europe and outside Europe

In order to calculate annual costs, the following parameters are used:

Table 14: Hypothesis for annualisation of investment costs - primary measures

p *Interest rate (%)*	4.0%	Recommended discount rate in the calculation of costs, Methodology Report GAINS, IIASA (International Institute for Applied Systems Analysis)
n *Equipment technical lifetime*	15	Data from car industry
Cop *Operating costs*	0	No data available

The total annual costs estimated per type of primary measures are detailed in table 15.

Table 15: Total annual costs - primary measures (based on investment costs only)

Primary measures	Annual cost (€/year)	Annual cost per unit of production *	
		(c€/year/m^2)	(€/year/car body)
Collection solvents	26 982 [17 988 - 44 971]	0.14 [0.09 – 0.23]	0.13 [0.09 – 0.22]
Optimisation of cleaning cycles	18 [0 - 63]	0.0001 [0.00 – 0.0003]	0.0001 [0.00 – 0.0003]
100% automation of primer, base coat, clear coat	899 411 [269 823 - 1 439 058]	4.64 [1.39 – 7.42]	4.50 [1.35 – 7.20]
Optimisation of colour change technology (base coat)	89 941 [53 965 – 116 923]	0.46 [0.28 – 0.60]	0.45 [0.27 – 0.58]
Innovative application technology (e.g bell-bell)	80 947 [62 959 – 89 941]	0.42 [0.32 – 0.46]	0.40 [0.31 – 0.45]
100% Automation of interior coating, with rotational bell atomisation and low los colour changers (base coat, clear coat)	1 409 630 [724 668 – 2 263 034]	7.27 [3.74 – 11.67]	7.05 [3.62 – 11.32]
Replacement of pneumatic guns application with robots by electrostatic bells (base coat)	63 512	0.33	0.32

* 97 m^2 / car body - 200 000 cars / year
c€: cents

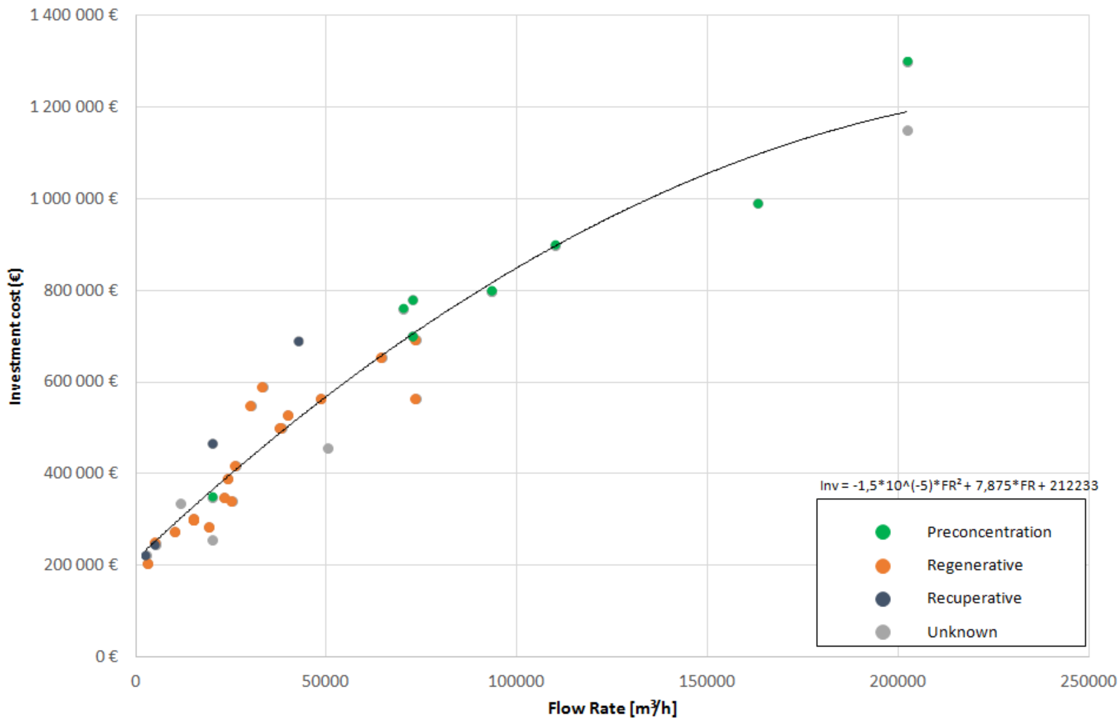
As already pointed out in Chapter 7.1 the reported list of possible primary measures is not exhaustive, and different measures are sometimes mutually exclusive. Investment costs seem to be project specific and annual operating costs were not submitted by the car industry, although there are some indications, that some measures like automation may lead to reduce payback periods (< 2 years) due to savings in wages.

8.3 Costs of secondary measures

The estimated costs of secondary measures are based on ERICCa_VOC modeling (input data presented in table 9).

Investment costs are estimated according to the air flow rates to be treated. A cost curve for thermal oxidisers and pre-concentrators with oxidisers has been established from supplier data (see figure 2 and eq. 9). With data collected, it can be considered that, when pre-concentration is advisable, the investment cost is similar with or without zeolite wheel because with pre-concentrator, a smaller oxidiser can be used. It has to be noted that investments for thermal recuperative and regenerative oxidisers are similar according to data collected.

Figure 2: Investment cost for thermal oxidizer and zeolite wheel according to the air flow rate to be treated



$\mathbf{Cinv} = -1,5 \times 10^{-5} \times (\text{air flow rate in } m^3/h)^2 + 7,875 \times (\text{air flow rate in } m^3/h) + 212\,233$	**Eq. 9**

Investment costs estimated with ERICCa_VOC are presented in table 16 for air flow rates equal to 30 000 Nm^3/h for a dryer and 200 000 Nm^3/h for a spray booth, with or without pre-concentration.

Investment costs considered in the tool are of two types: investment cost for device(s) and for installation expenditure (ducts, modification of building). For total investment costs associated with auxiliaries in order to have a technique ready to work, a factor of 1.85 is applied.

Table 16: Investment costs - secondary measures

	Air flow rates	**Investment cost**			**Reference**
		Device(s)	**Installation expenditure**	**Total**	
	Nm^3/h	**million €**	**million €**	**million €**	
Spray booth	200 000	1.19	1.01	2.20	[7]
Dryer	30 000	0.43	0.37	0.80	[7]

[7] ERICCa_VOC

In order to calculate annual total costs, the following parameters are used:

Table 17: Hypothesis for annualisation of investment costs - secondary measures

p *Interest rate (%)*	4.0%	Recommended discount rate in the calculation of costs, Methodology Report GAINS, IIASA (International Institute for Applied Systems Analysis)
n *Equipment technical lifetime*	15	Suppliers data
Cop *Operating costs*	Fixed + variable	*Fixed operating costs:* annual insurance and tax cost and annual maintenance cost (without labour) *Variable operating costs:* annual labour, electricity and natural gas costs

Annual investment costs and operating costs estimated with ERICCa_VOC are presented in tables 18 and 19 respectively. With the objective to compare the costs between the primary measures, secondary and a change for a new paint shop, the investment and operating costs are presented separately.

The total annual costs (investment and operating costs) are presented in table 20.

Table 18: Annualised investment costs - secondary measures (with or without preconcentration)

	Air flow rates Nm^3/h	**Annual investment cost (installation expenditure cost included) (million €/year)**	**Annual investment cost per unit of production ***		**Reference**
			(c€/year/m^2)	**(€/year/car body)**	
Spray booth	200 000	2.20	0.83	0.81	[7]
Dryer	30 000	0.80	0.31	0.30	[7]

c€: cents

* 97 m^2 / car body - 200 000 cars / year – 60 jobs per hour

[7] ERICCa_VOC

Table 19: Annual operating costs - secondary measures

			Annual operating cost (€/year)							Annual operating cost per unit of production *		Reference
			Variable				Fixed		Total			
			Labour	Electricity	Natural gas	Heat benefits theorically possible	Insurance and tax	Maintenance (without labour)		(c€/year/m²)	(€/year/car body)	
S1 ***SB***	Primer	spray booth	5 395	36 837	0	X	65 891	43 928	152 051	0.78	0.76	[7]
		dryer	5 395	15 243	17 797		24 142	16 094	78 671	0.41	0.39	[7]
	Base coat	spray booth	5 395	101 619	104 601		65 891	43 928	321 435	1.66	1.61	[7]
	Clear coat	spray booth	5 395	101 619	110 831		65 891	43 928	327 664	1.69	1.64	[7]
		dryer	5 395	15 243	10 859		24 142	16 094	71 734	0.37	0.36	[7]
S2A ***SB-MIX***	Primer	spray booth	5 395	36 837	3 926		65 891	43 928	155 977	0.80	0.78	[7]
		dryer	5 395	15 243	23 087		24 142	16 094	83 961	0.43	0.42	[7]
	Base coat	spray booth	5 395	101 619	117 588		65 891	43 928	334 422	1.72	1.67	[7]
	Clear coat	spray booth	5 395	101 619	123 501		65 891	43 928	340 335	1.75	1.70	[7]
		dryer	5 395	15 243	14 122		24 142	16 094	74 996	0.39	0.37	[7]
S2B ***SB-MIX***	Primer	spray booth	5 395	36 837	0	X	65 891	43 928	152 051	0.78	0.76	[7]
		dryer	5 395	15 243	17 971		24 142	16 094	78 845	0.41	0.39	[7]
	Base coat	spray booth	5 395	36 837	0	X	65 891	43 928	152 051	0.78	0.76	[7]
	Clear coat	spray booth	5 395	36 837	0	X	65 891	43 928	152 051	0.78	0.76	[7]
		dryer	5 395	15 243	15 262		24 142	16 094	76 137	0.39	0.38	[7]
S3 ***WB***	Primer	spray booth	5 395	36 837	2 131		65 891	43 928	154 182	0.79	0.77	[7]
		dryer	5 395	15 243	22 390		24 142	16 094	83 264	0.43	0.42	[7]
	Base coat	spray booth	5 395	36 837	0	X	65 891	43 928	152 051	0.78	0.76	[7]
	Clear coat	spray booth	5 395	101 619	121 917		65 891	43 928	338 751	1.75	1.69	[7]
		dryer	5 395	15 243	13 694		24 142	16 094	74 569	0.38	0.37	[7]
S4 ***Integrated process***	Base coat	spray booth	5 395	36 837	0	X	65 891	43 928	152 051	0.78	0.76	[7]
	Clear coat	spray booth	5 395	101 619	131 843		65 891	43 928	348 677	1.80	1.74	[7]
		dryer	5 395	15 243	16 244		24 142	16 094	77 119	0.40	0.39	[7]

* 97 m² / car body - 200 000 cars / year – 60 jobs per hour

[7] ERICCa_VOC

Table 20: Annual operating and annualised investment costs - secondary measures

			Total annual investment cost (€/year)	Total annual operating cost (€/year)	Total annual cost (€/year)	Total annual cost per unit of production		Reference
						(c€/year/m^2)	(€/year/car body)	
S1 ***SB***	Primer	spray booth	161 614	152 051	313 665	1.62	1.57	[7]
		dryer	59 213	78 671	137 883	0.71	0.69	[7]
	Base coat	spray booth	161 614	321 435	483 048	2.49	2.42	[7]
	Clear coat	spray booth	161 614	327 664	489 278	2.52	2.45	[7]
		dryer	59 213	71 734	130 946	0.67	0.65	[7]
S2A ***SB-MIX***	Primer	spray booth	161 614	155 977	317 591	1.64	1.59	[7]
		dryer	59 213	83 961	143 173	0.74	0.72	[7]
	Base coat	spray booth	161 614	334 422	496 036	2.56	2.48	[7]
	Clear coat	spray booth	161 614	340 335	501 949	2.59	2.51	[7]
		dryer	59 213	74 996	134 209	0.69	0.67	[7]
S2B ***SB-MIX***	Primer	spray booth	161 614	152 051	313 665	1.62	1.57	[7]
		dryer	59 213	78 845	138 058	0.71	0.69	[7]
	Base coat	spray booth	161 614	152 051	313 665	1.62	1.57	[7]
	Clear coat	spray booth	161 614	152 051	313 665	1.62	1.57	[7]
		dryer	59 213	76 137	135 349	0.70	0.68	[7]
S3 ***WB***	Primer	spray booth	161 614	154 182	315 796	1.63	1.58	[7]
		dryer	59 213	83 264	142 477	0.73	0.71	[7]
	Base coat	spray booth	161 614	152 051	313 665	1.62	1.57	[7]
	Clear coat	spray booth	161 614	338 751	500 365	2.58	2.50	[7]
		dryer	59 213	74 569	133 781	0.69	0.67	[7]
S4 ***Integrated process***	Base coat	spray booth	161 614	152 051	313 665	1.62	1.57	[7]
	Clear coat	spray booth	161 614	348 677	510 290	2.63	2.55	[7]
		dryer	59 213	77 119	136 331	0.70	0.68	[7]

[7] ERICCa_VOC

8.4 Costs of new paint shops

The estimated costs of new paint shops are based on data provided by car manufacturers who set up this type of paint shops. In order to define possible changes for a new paint shop and VOC reduction associated based on real life cases, data were collected from some 13 plants (9 in Europe and 4 outside Europe). On 13 plants, 6 correspond to a modification of the existing paint shop and 7 to the construction of a new paint shop. The summary of these data are presented in the table 21.

The operating costs or profits are difficult to estimate by car industries for new paint shop. Only investment costs are consequently considered. They include:

- building,
- paint application devices,
- spray booth,
- oven/dryer,
- waste gases treatment,
- waste water treatment.

In case of retrofitting (6 examples) cost for demolishing of the old paint shop and technical modifications made in the existing site to connect the new paint line to the existing production infrastructure were taken into account.

The investment costs provided by the car manufacturers reported in job per hour (in million € / job per hour) have been multiplied by the production of the reference installation (60 jobs per hour) to obtain comparable investment costs (in million €).

Table 21: Investment costs - new paint shops

Change for a new paint shop	Investment cost (million €/job per hour)	Investment cost (million €) *	Number of sites for data collection	References
1 (SB) to 3 (WB) *Switching the primer and the base coat from solvent-based to water-based coating*	2.1	128.0	1	[8]
1 (SB) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating and remove the primer*	0.9 [0.6 – 12]	52.7 [35.6 – 69.7]	2	[8]
2 (SB-MIX) to 3 (WB) *Switching the primer or the base coat from solvent-based to water-based coating*	0.3 [0.1 – 0.5]	18.0 [6.0 – 30.0]	2	[8]
2 (SB-MIX) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating or remove the primer*	3.2	190.9	1	[8]
New complete paint shop 3 (WB)	3.5	211.8	1	[8]
New complete paint shop 4 (Integrated process)	4.0 [2.0 – 8.3]	238.0 [120.0 – 495.0]	6	[8]

* Estimated for a technical capacity of 60 jobs per hour

[8] Data collection from 13 plants in Europe and outside Europe

In order to calculate annual costs, the following parameters are used:

Table 22: Hypothesis for annualisation of investment cost – new paint shops

p *Interest rate (%)*	4.0%	Recommended discount rate in the calculation of costs, Methodology Report GAINS, IIASA (International Institute for Applied Systems Analysis)
n *Equipment technical lifetime*	15	Data from car industry
Cop *Operating costs*	0	No data available

The annual costs estimated by type of new paint shop are detailed in table 23.

Table 23: Annual costs - new paint shops (based on investment costs only)

Change for a new paint shop	**Annual cost (million €/year)**	**Annual cost per unit of production ***	
		(c€/year/m^2)	**(€/year/car body)**
1 (SB) to 3 (WB) *Switching the primer and the base coat from solvent-based to water-based coating*	11.5	59.3	57.9
1 (SB) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating and remove the primer*	4.7 [3.2 – 6.3]	24.4 [16.5 – 32.3]	23.7 [16.0 – 31.4]
2 (SB-MIX) to 3 (WB) *Switching the primer or the base coat from solvent-based to water-based coating*	1.6 [0.5 – 2.7]	8.3 [2.8 – 13.9]	8.1 [2.7 – 13.5]
2 (SB-MIX) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating or remove the primer*	17.2	88.5	85.9
New complete paint shop 3 (WB)	19.0	98.2	95.2
New complete paint shop 4 (Integrated process)	21.4 [10.8 – 44.5]	110.3 [55.6 – 229.5]	107.0 [54.0 – 222.6]

* 97 m^2 / car body - 200 000 cars / year – 60 jobs per hour

9 Cost effectiveness analysis

From total annual costs and total VOC emissions abated, associated with the implementation ratios of a reduction measure (primary, secondary or change for a new paint shop), cost effectiveness can be calculated from the following formula:

Cost effectiveness (€/g /m^2) = annual cost (€/year)/annual reduction of VOC emissions (g/m^2/year)

Cost effectiveness (€/t VOC avoided) = annual cost (€/year)/ annual reduction of VOC emissions (t/year)

g/m^2 corresponds to grams of organic solvent emitted in relation to the surface area of product in m^2. For the translation from g/m^2 to t of VOC avoided, the following hypotheses are considered:

Table 24: Hypothesis for cost effectiveness calculation

Annual production	200 000 car bodies per year (passenger cars only), corresponding to 2x8 shift works loaded (60 jobs per hour)
Electrophoretic coating area	97 m^2

9.1 Cost effectiveness analysis of primary measures

To make the cost effectiveness analysis, annual costs from table 15 and reduction of annual VOC emissions from table 7 are used.

The results for cost effectiveness analysis of primary measures are presented in table 25.

Table 25: Cost effectiveness - primary measures

Primary measures	**Cost effectiveness**	
	(€/g/m^2)	**(€/t VOC avoided)**
Collection of solvents	11 243 [3 997 – 89 941]	580 [206 – 4 636]
Optimisation of cleaning cycles	30 [0 – 1 259]	1,5 [0 – 64,9]
100% automation of primer, base coat, clear coat	749 509 [224 853 – 1 308 234]	38 634 [11 590 – 67 435]
Optimisation of colour change technology (base coat)	179 882 [49 059 – 1 670 335]	9 272 [2 529 – 86 100]
Innovative application technology (e.g bell-bell)	101 184 [62 959 – 149 902]	5 216 [3 245 - 7 727]
100% Automation of interior coating, with rotational bell atomisation and low los colour changers (base coat, clear coat)	542 165 [120 778 – 2 828 793]	27 947 [6 226 – 145 814]
Replacement of pneumatic guns application with robots by electrostatic bells (base coat)	59 830	14 234

9.2 Cost effectiveness analysis of secondary measures

To make the cost effectiveness analysis, annual costs from table 20 and reduction of annual VOC emissions from table 10 are used.

Table 26: Cost effectiveness - secondary measures

			Cost effectiveness analysis					
			Investment cost		**Operating cost**		**Total cost**	
			(€/g/m²)	**(€/t VOC avoided)**	**(€/g/m²)**	**(€/t VOC avoided)**	**(€/g/m²)**	**(€/t VOC avoided)**
S1 ***SB***	Primer	spray booth	27 783	1 347	26 139	1 347	53 923	2 780
		dryer	26 374	1 806	35 041	1 806	61 414	3 166
	Base coat	spray booth	8 291	850	16 491	850	24 782	1 277
	Clear coat	spray booth	9 243	966	18 740	966	27 983	1 442
		dryer	13 217	825	16 012	825	29 229	1 507
		TOTAL	**84 908**	**5 795**	**112 422**	**5 795**	**197 330**	**10 172**
S2A ***SB-MIX***	Primer	spray booth	115 876	5 765	111 835	5 765	227 712	11 738
		dryer	109 476	8 002	155 232	8 002	264 708	13 645
	Base coat	spray booth	10 558	1 126	21 847	1 126	32 404	1 670
	Clear coat	spray booth	12 058	1 309	25 393	1 309	37 451	1 930
		dryer	17 269	1 127	21 872	1 127	39 140	2 018
		TOTAL	**265 237**	**17 329**	**336 178**	**17 329**	**601 415**	**31 001**
S2B ***SB-MIX***	Primer	spray booth	28 449	1 380	26 765	1 380	55 214	2 846
		dryer	27 050	1 857	36 019	1 857	63 069	3 251
	Base coat	spray booth	33 223	1 611	31 258	1 611	64 481	3 324
	Clear coat	spray booth	13 535	656	12 735	656	26 270	1 354
		dryer	19 341	1 282	24 869	1 282	44 209	2 279
		TOTAL	**121 598**	**6 786**	**131 645**	**6 786**	**253 243**	**13 054**
S3 ***WB***	Primer	spray booth	81 913	4 028	78 146	4 028	160 059	8 250
		dryer	77 363	5 608	108 787	5 608	186 150	9 595
	Base coat	spray booth	32 319	1 567	30 407	1 567	62 726	3 233
	Clear coat	spray booth	11 616	1 255	24 348	1 255	35 964	1 854
		dryer	16 601	1 078	20 907	1 078	37 508	1 933
		TOTAL	**219 812**	**13 536**	**262 595**	**13 536**	**482 407**	**24 866**
S4 ***Integrated process***	Base coat	spray booth	28 969	1 405	27 255	1 405	56 224	2 898
	Clear coat	spray booth	15 082	1 677	32 540	1 677	47 622	2 455
		dryer	21 570	1 448	28 092	1 448	49 662	2 560
		TOTAL	**65 621**	**4 530**	**87 887**	**4 530**	**153 508**	**7 913**

9.3 Cost effectiveness analysis of new paint shop

To make the cost effectiveness analysis complete, annual costs for the establishment of a complete new paint shop were integrated with cases of change from existing paint shop (see table 23).

Regarding the reduction of annual VOC emissions, the data are not available in all cases. For reasons of consistency, the potential VOC emissions reduction based on SMP are used (see table 11).

Table 27: Cost effectiveness - new paint shops

Change for a new paint shop	**Cost effectiveness**	
	(€/g/m^2)	**(€/t VOC avoided)**
1 (SB) to 3 (WB) *Switching the primer and the base coat from solvent-based to water-based coating*	570 959 [430 197 – 711 722]	29 341 [22 175 – 36 687]
1 (SB) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating and remove the primer*	481 716 [114 341 – 1 780 834]	24 831 [4 611 – 64 127]
2 (SB-MIX) to 3 (WB) *Switching the primer or the base coat from solvent-based to water-based coating*	1 203 668 [87 446 – 3 086 327]	62 045 [4 508 – 159 089]
2 (SB-MIX) to 4 (Integrated process) *Switching the base coat from solvent-based to water-based coating or remove the primer*	1 368 802 [710 213 – 2 929 630]	70 557 [36 609 – 151 012]

10 Cross media effects

Cross media effects are evaluated for secondary measures only due to insufficient data for primary measure.

In ERICCa_VOC, the emissions of greenhouse gases (CO_2, N_2O, CH_4) and pollutants (VOC, NO_X) associated with thermal oxidation are estimated.

Emissions of greenhouse gases are linked to consumption of natural gas for direct emissions and consumption of electricity for indirect emissions. Emissions of pollutants are due to combustion of the oxidiser (the indirect emissions from electricity consumption are not taken into account).

Table 28: Cross media effects – secondary measures

			Greenhouse gases					Pollutants		Ref.
			Direct emissions from natural gas consumption				Indirect emissions from electricity consumption	Emissions from combustion		
			CO_2	CH_4	N_2O	TOTAL	Indirect CO_2	CO	NO_X	
			kg eq CO_2/year					kg/year	eq NO_2 kg/year	
S1 ***SB***	Primer	spray booth	0	0	0	0	180 963	2 500	600	[7]
		dryer	168 478	75	89	168 643	74 881	7 499	1 800	[7]
	Base coat	spray booth	990 242	441	526	991 209	499 209	49 995	11 999	[7]
	Clear coat	spray booth	1 049 219	468	557	1 050 244	499 209	49 995	11 999	[7]
		dryer	102 805	46	55	102 905	74 881	7 499	1 800	[7]
		TOTAL	**2 310 744**	**1 030**	**1 227**	**2 313 001**	**1 329 145**	**117 488**	**28 197**	
S2A ***SB-MIX***	Primer	spray booth	37 167	17	20	37 203	180 963	2 500	600	[7]
		dryer	218 558	97	116	218 772	74 881	7 499	1 800	[7]
	Base coat	spray booth	1 113 193	496	591	1 114 281	499 209	49 995	11 999	[7]
	Clear coat	spray booth	1 169 171	521	621	1 170 313	499 209	49 995	11 999	[7]
		dryer	133 692	60	71	133 823	74 881	7 499	1 800	[7]
		TOTAL	**2 671 782**	**1 191**	**1 419**	**2 674 392**	**1 329 145**	**117 488**	**28 197**	
S2B ***SB-MIX***	Primer	spray booth	0	0	0	0	180 963	2 500	600	[7]
		dryer	170 128	76	90	170 294	74 881	7 499	1 800	[7]
	Base coat	spray booth	0	0	0	0	180 963	2 500	600	[7]
	Clear coat	spray booth	0	0	0	0	180 963	2 500	600	[7]
		dryer	144 488	64	77	144 629	74 881	7 499	1 800	[7]
		TOTAL	**314 616**	**140**	**167**	**314 923**	**692 653**	**22 498**	**5 399**	
S3 ***WB***	Primer	spray booth	20 174	9	11	20 193	180 963	2 500	600	[7]
		dryer	211 961	94	113	212 168	74 881	7 499	1 800	[7]
	Base coat	spray booth	0	0	0	0	180 963	2 500	600	[7]
	Clear coat	spray booth	1 154 177	514	613	1 155 304	499 209	49 995	11 999	[7]
		dryer	129 644	58	69	129 770	74 881	7 499	1 800	[7]
		TOTAL	**1 515 956**	**676**	**805**	**1 517 436**	**1 010 899**	**69 993**	**16 798**	
S4 ***Integrated process***	Base coat	spray booth	0	0	0	0	180 963	2 500	600	[7]
	Clear coat	spray booth	1 248 139	556	663	1 249 359	499 209	49 995	11 999	[7]
		dryer	153 784	69	82	153 934	74 881	7 499	1 800	[7]
		TOTAL	**1 401 924**	**625**	**745**	**1 403 293**	**755 054**	**59 994**	**14 399**	

[7] ERICCa_VOC

11 Conclusions

Five reference plants have been defined in order to represent all families of paint shops (SB, SB-MIX, WB, integrated process[5]) (see table 2).

These five reference plants have in common the following parameters:

- Annual production: 200 000 car bodies per year (passenger cars only), corresponding to 2x8 shift works loaded (60 jobs per hour)
- Electrophoretic coating area: 97 m^2/car

Three options to reduce VOC emissions for paint shops are considered in this study:

1. Primary measures corresponding to the reduction of VOC emissions at the source (reduction of solvent consumption or improved collection of solvent),
2. Secondary measures to treat waste gases containing VOC (end of pipe techniques),
3. Change for a new paint shop (which allows to employ water based paint systems and advanced paint application and waste gas treatment techniques).

For each type of measures, parameters followed are estimated:

1. VOC emission reduction potentials based on SMP or modeling and on case studies,
2. Annual costs based on case studies and modeling,
3. Cost effectiveness analysis linking VOC emission reduction and annual costs.

Tables 29 and 30 present synthesis of VOC emission reductions and cost effectiveness analysis for all reference installations and measures.

[5] Families are: SB: entirely solvent-based coating, WB: primer and base coat are water based, SB-MIX: either primer or base coats are solvent based, Integrated process (IP): primerless paint shop with water based base coat.

Table 29: Synthesis of VOC emission reduction based on SMP or modeling and case studies (tables 3/6/7/8/11/12)

VOC emission of reference installations	**1** ***SB***	**2** ***SB-MIX***	**3** ***WB***	**4** ***Integrated process***	***Ref.***
VOC emission (g/m^2) Average [Min – Max]	37,8 [16,8 - 50,3]	28.7 [12.5 - 48.2]	18.6 [6.0 - 30.5]	20.5 [8.9 - 32.1]	[4]

Primary measures (SMP)	**1** ***SB***	**2** ***SB-MIX***	**3** ***WB***	**4** ***Integrated process***	***Ref.***
Potential of VOC emission reduction (g/m^2)	26.2	4.5	8.7	7.0	[5]

Primary measures (case studies)	***Reduction of VOC emission (g/m^2)***	***Ref.***
Collection of solvents	2.4 [0.5 – 4.5]	[6]
Optimisation of cleaning cycles	0.6 [0.05 – 1.8]	[6]
100% automation of primer, base coat, clear coat	1.2 [1.1 – 1.2]	[6]
Optimisation of colour change technology (base coat)	0.5 [0.07 – 1.1]	[6]
Innovative application technology (e.g bell-bell)	0.8 [0.6 – 1]	[6]
100% Automation of interior coating, with rotational bell atomisation and low loss colour changers (base coat, clear coat)	2.6 [0.8 – 6]	[6]
Replacement of pneumatic guns application with robots by electrostatic bells (base coat)	0.23	[6]

Secondary measures (SMP)	**1** ***SB***	**2** ***SB-MIX***	**3** ***WB***	**4** ***Integrated process***	***Ref.***
Potential VOC emission reduction with implementation of air treatment on ovens/dryers (g/m^2) O5 $_{\text{air treatment on dryers/ovens}}$	11.2 [9.0 – 16.6]	5.8 [1.5 – 8.0]	9.7 [6.1 – 15.3]	7.1 [4.1 – 12.5]	[5]
Potential VOC emission reduction with implementation of air treatment on ovens/dryers and spray booths (g/m^2) O5 $_{\text{air treatment on dryers/ovens and spray booths}}$	14.6 [10.0 – 19.2]	14.0	11.6	1.5	[5] [4]

Secondary measures (modeling)		**1** ***SB***	**2A** ***SB-MIX***	**2B** ***SB-MIX***	**3** ***WB***	**4** ***Integrated process***	***Ref.***
Primer	Spray booth	5.8	1.4	5.7	2.0	-	[6]
	Dryer	2.2	0.5	2.2	0.8	-	[6]
Base coat	Spray booth including flash off/ intermediate dryer	19.5	15.3	4.9	5.0	5,6	[6]
Clear coat	Spray booth	17.5	13.4	11.9	13.9	10,7	[6]
	Dryer	4.5	3.4	3.1	3.6	2,7	[6]
	Maximum reduction of VOC emission estimated (sum)	*49,5*	*34.1*	*27.7*	*25.2*	*19.0*	-

Change for new paint shops (SMP) **Comparison between:**	***1 (SB) and 3 (WB)***	***1 (SB) and 4 (Integrated process)***	***2 (SB-MIX) and 3 (WB)***	***2 (SB-MIX) and 4 (Integrated process)***	***Ref.***
Potential of VOC reduction emission (g/m^2)	26.8	35.8	6.2	15.2	[5]

Change for new paint shops (case studies) **Comparison between:**	***1 (SB) and 3 (WB)***	***1 (SB) and 4 (Integrated process)***	***2 (SB-MIX) and 3 (WB)***	***2 (SB-MIX) and 4 (Integrated process)***	***Ref.***
VOC reduction emission (g/m^2)	41.0	27 [25 – 28]	-	15.0	[8]

Table 30: Synthesis of costs effectiveness analysis (tables 25/26/27)

Primary measures *(based on investment costs only)*	**(€/g/m²)**	**(€/t VOC avoided)**
Collection of solvents	11 243 [3 997 – 89 941]	580 [206 – 4 636]
Optimisation of cleaning cycles	30 [0 – 1 259]	1,5 [0 – 64,9]
100% automation of primer, base coat, clear coat	749 509 [224 853 – 1 308 234]	38 634 [11 590 – 67 435]
Optimisation of colour change technology (base coat)	179 882 [49 059 – 1 670 335]	9 272 [2 529 – 86 100]
Innovative application technology (e.g bell-bell)	101 184 [62 959 – 149 902]	5 216 [3 245 - 7 727]
100% Automation of interior coating, with rotational bell atomisation and low los colour changers (base coat, clear coat)	542 165 [120 778 – 2 828 793]	27 947 [6 226 – 145 814]
Replacement of pneumatic guns application with robots by electrostatic bells (base coat)	59 830	14 234

Secondary measures *(based on investment and operating costs)*			**Investment cost**		**Operating cost**		**Total cost**	
			(€/g/m²)	**(€/t VOC avoided)**	**(€/g/m²)**	**(€/t VOC avoided)**	**(€/g/m²)**	**(€/t VOC avoided)**
S1 ***SB***	Primer	spray booth	27 783	1 347	26 139	1 347	53 923	2 780
		dryer	26 374	1 806	35 041	1 806	61 414	3 166
	Base coat	spray booth	8 291	850	16 491	850	24 782	1 277
	Clear coat	spray booth	9 243	966	18 740	966	27 983	1 442
		dryer	13 217	825	16 012	825	29 229	1 507
		TOTAL	**84 908**	**5 795**	**112 422**	**5 795**	**197 330**	**10 172**
S2A ***SB-MIX***	Primer	spray booth	115 876	5 765	111 835	5 765	227 712	11 738
		dryer	109 476	8 002	155 232	8 002	264 708	13 645
	Base coat	spray booth	10 558	1 126	21 847	1 126	32 404	1 670
	Clear coat	spray booth	12 058	1 309	25 393	1 309	37 451	1 930
		dryer	17 269	1 127	21 872	1 127	39 140	2 018
		TOTAL	**265 237**	**17 329**	**336 178**	**17 329**	**601 415**	**31 001**
S2B ***SB-MIX***	Primer	spray booth	28 449	1 380	26 765	1 380	55 214	2 846
		dryer	27 050	1 857	36 019	1 857	63 069	3 251
	Base coat	spray booth	33 223	1 611	31 258	1 611	64 481	3 324
	Clear coat	spray booth	13 535	656	12 735	656	26 270	1 354
		dryer	19 341	1 282	24 869	1 282	44 209	2 279
		TOTAL	**121 598**	**6 786**	**131 645**	**6 786**	**253 243**	**13 054**
S3 ***WB***	Primer	spray booth	81 913	4 028	78 146	4 028	160 059	8 250
		dryer	77 363	5 608	108 787	5 608	186 150	9 595
	Base coat	spray booth	32 319	1 567	30 407	1 567	62 726	3 233
	Clear coat	spray booth	11 616	1 255	24 348	1 255	35 964	1 854
		dryer	16 601	1 078	20 907	1 078	37 508	1 933
		TOTAL	**219 812**	**13 536**	**262 595**	**13 536**	**482 407**	**24 866**
S4 ***Integrated process***	Base coat	spray booth	28 969	1 405	27 255	1 405	56 224	2 898
	Clear coat	spray booth	15 082	1 677	32 540	1 677	47 622	2 455
		dryer	21 570	1 448	28 092	1 448	49 662	2 560
		TOTAL	**65 621**	**4 530**	**87 887**	**4 530**	**153 508**	**7 913**

Change for a new paint shop *(based on investment costs only)*	**(€/g/m²)**	**(€/t VOC avoided)**
1 (SB) to 3 (WB)	570 959 [430 197 – 711 722]	29 341 [22 175 – 36 687]
1 (SB) to 4 (Integrated process)	481 716 [114 341 – 1 780 834]	24 831 [4 611 – 64 127]
2 (SB-MIX) to 3 (WB)	1 203 668 [87 446 – 3 086 327]	62 045 [4 508 – 159 089]
2 (SB-MIX) to 4 (Integrated process)	1 368 802 [710 213 – 2 929 630]	70 557 [36 609 – 151 012]

12 References

[1] Directive 2007/46/EC establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles.

[2] Overview on paint shop technology:

- Streitberger, H.-J., Dössel, K.-F., Eds. *Automotive paints and coatings*, 2., completely rev. and extended ed.; Wiley-VCH-Verl.: Weinheim, 2008.
- Toda, K., Salazar, A., Saito, K., Eds. *Automotive Painting Technology;* Springer Netherlands: Dordrecht, 2013.
- Kommission Reinhaltung der Luft (KRdL). *Emissionsminderung - Anlagen zur Serienlackierung von Automobilkarosserien - Emission control - High-volume car body painting plants;* Beuth Verlag: Düsseldorf, 2013.
- Akafuah, N. et al. *Evolution of the Automotive Body Coating Process; Coatings – a review*. Coatings, 2016 (2).

[3] Directive 2010/75/EU of the European parliament and of the council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

[4] ACEA 2015

ACEA Paint Shop Survey. Consumption and emission data of EU vehicle paint shops in 2012 (with updates in 2013 und 2014); European Automobile Manufacturer's Association (ACEA): Brussels, 2015 (unpublished),

[5] SMP 2014

Solvent management plans of vehicle paint shops in Europe. Confidential communications from3 ACEA members

[6] Primary measures

Reduction of VOC emissions and investment costs associated by type of primary measure provided by 22 plants in Europe. Confidential communications from 2 ACEA members.

[7] ERICCa_VOC (0.38)

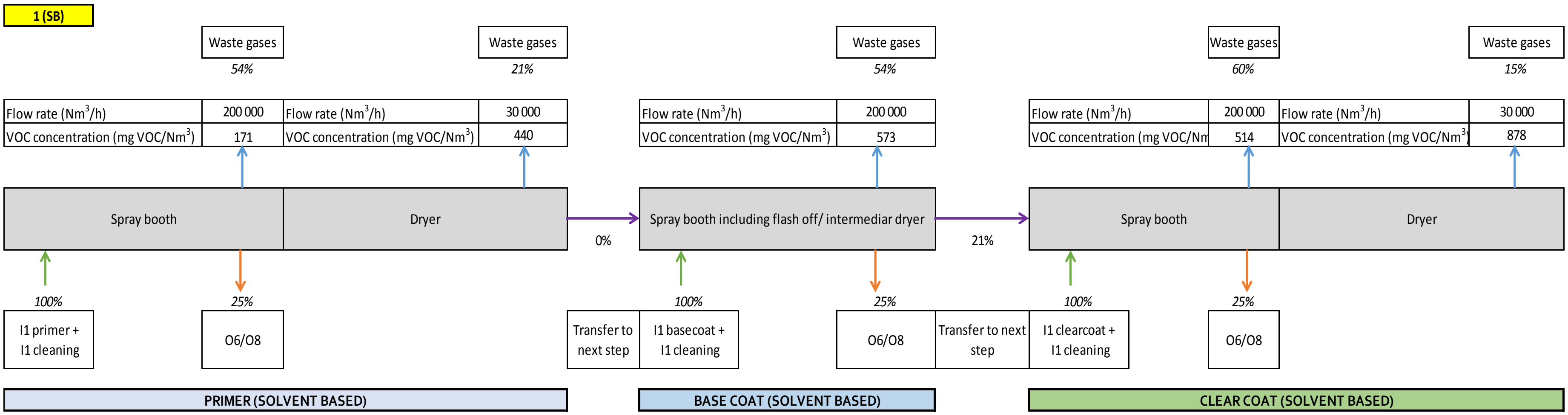
Tool developed in the scope of this project, is able to estimate the costs (investments, fixed and variable operating costs and total annual costs) associated with different reduction techniques such as thermal oxidizer (secondary measure).

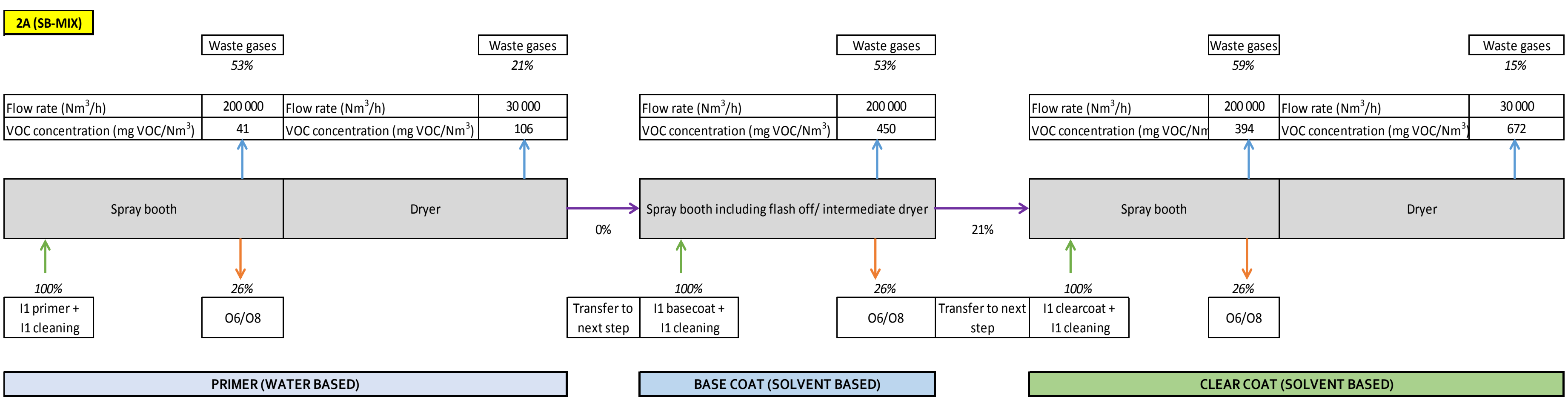
[8] New paint shops

Reduction of VOC emissions and investment costs associated by type of new paint shop provided by 13 plants (9 in Europe and 4 outside Europe). On 13 plants, 6 correspond to a modification of the paint shop and 7 to the construction of a new paint shop. Data on reduction of VOC emissions are available for four plants of six. Confidential communications from ACEA.

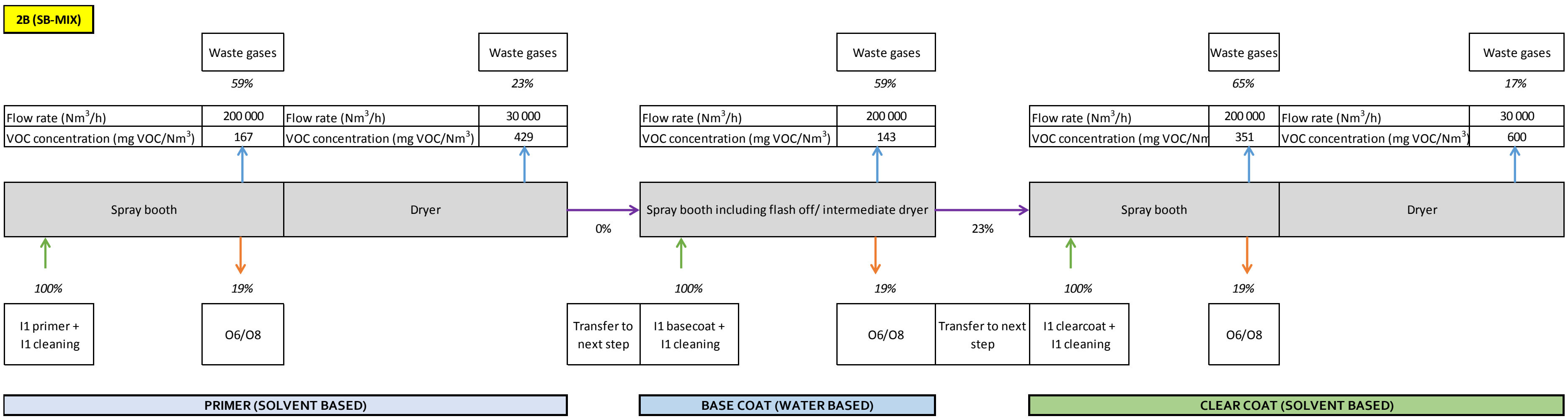
[9] EU Commission, *Cross media and economic assessment*, 2006

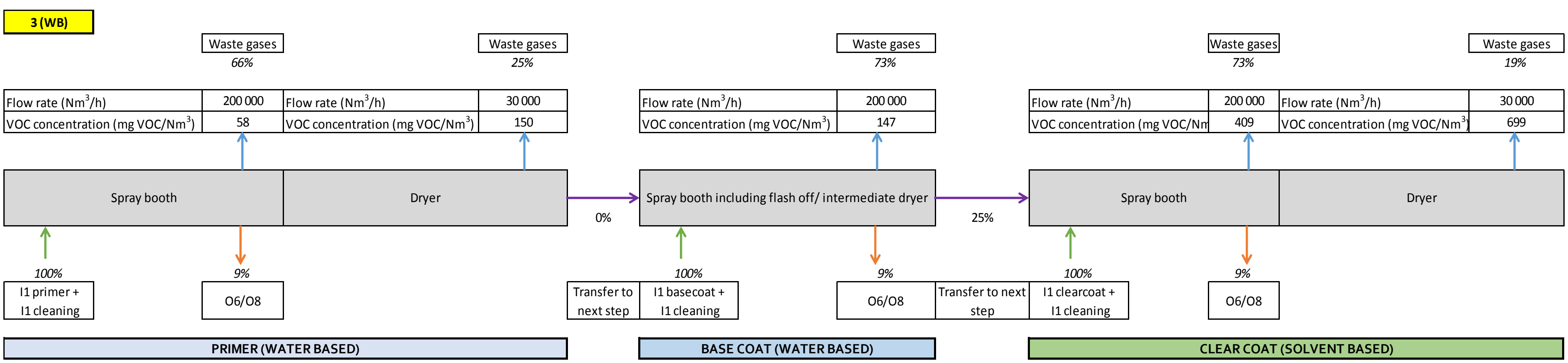
Annex 1 - Input Data for ERICCa-VOC



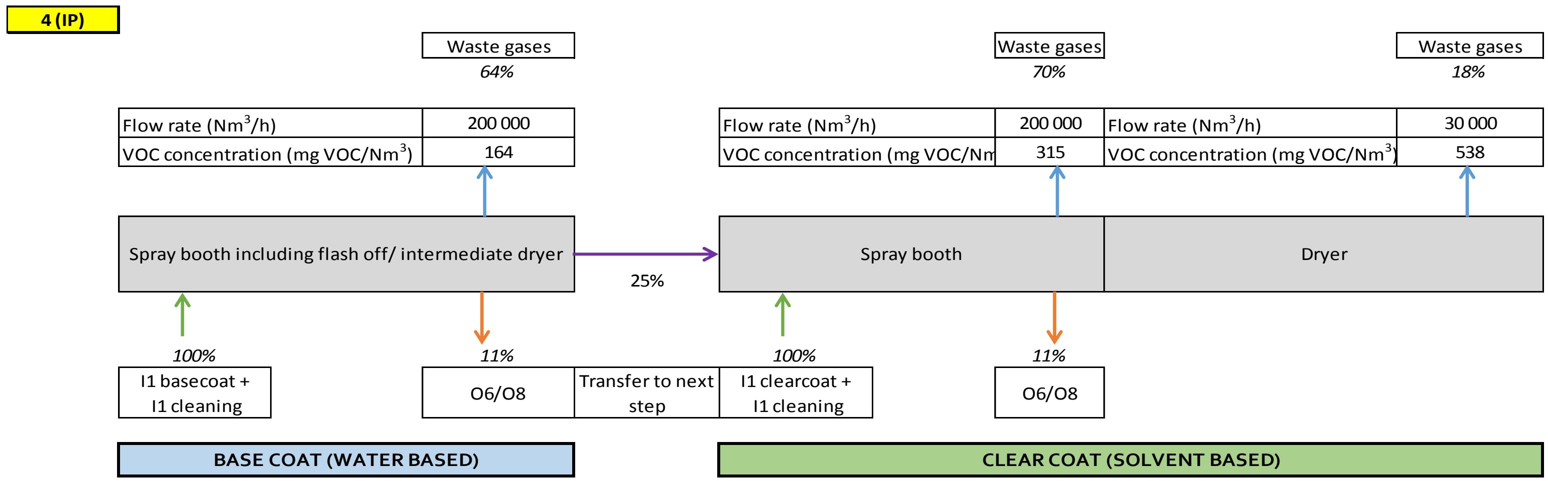


VOC Abatement: car coating 30-11-2016





VOC Abatement: car coating 30-11-2016



Annex 2 - Supplementary information on car coating process

In order to write this Annex, bibliographic references [2] listed chapter 11 were used.

Pretreatment

The pretreatment of car bodies manufactured from different metals is mandatory for state-of-the-art corrosion protection and provides best adhesion for electrodeposition coatings.

The process comprises several stages, namely, degreasing, rinsing, activation, phosphating, rinsing, passivation (optionally), and a final demineralized water rinsing.

Degreasing solubilizes grease, for example, deep-drawing greases, oil, wax, and other contaminations acquired from the earlier working processes. Phosphating following after a purging process, serves as a temporary corrosion protection, and improves the adhesiveness of the paint film when it is applied.

Cleaning agents are aqueous alkaline detergent solutions which are applied at elevated temperatures, followed by cascading rinse baths.

This preliminary step does not involve use of solvents

E-coat

E-coat, short for electrolytic coating or cathodic dip coating. Electrocoating covers all dip painting processes, where the paint precipitates on the workpiece owing to chemical conversion and associated coagulation of the binder. These conversions are caused by an electric current flow from an external electrode via the conductive paint, to the workpiece.

The organic coating with a dry-film thickness of ca. 20 µm at exterior surfaces delivers rust-protection and an even film as substrate for the following spray applications. The car body acts as cathode (negatively charged) and the anodes are positioned at the bottom and side walls of the tank. The advantage of the dip process is that corrosion protection is provided not only for visible surfaces but also for hidden areas and cavities. The surplus coat is rinsed off from the car body and the e-coat film is cured in a drying oven (typically 15 min at 180 °C).

Electrocoat paints are water soluble (suspensions of binders and pigments in d.i.(deionized) water) with only low proportions of organic solvents (approximately 3%).

Sealing and damping

Additional rust and stone chipping protection for the underbody and seam sealing is applied in the sealing and damping (SD) segment. The paste coatings are applied manually or with robots. In most cases noise damping material either as custom-tailored pads or as sprayable paste is applied in this section also. The gelling reaction starts in the successive dryer (typically 120 °C) and is ultimately completed in the primer oven.

The paste coatings are with very low VOC contents (2 - 5 %), Damping material usually has no VOCs.

Primer

The primer (in non EU countries often called primer surfacer) layer is applied on top of the electrocoat and protects the cataphoretic electrocoating film from ultra violet (UV) radiation, serves as a surface smoothing primer for the following top coat film, and reduces the risk of damage to the layers below, in case of stone chips. Usually 2 to 4 different colours are used which are adapted to the base coat colours. Dry film thickness varies between 20 to 40 µm.

Three technologies have been established:

- solventbased primer, VOC content 42 +/- 8 %
- waterbased primer, VOC content 9 +/- 3 %
- powder primer (not used in Europe)

The primer coat is cured in a dryer oven (typically 15 min at 160 °C)

While pretreatment and electrocoat are required for corrosion protection, and primer for UV protection, leveling of structure and stone chip protection, the main function of the top coat layer(s) is to give colour and durability to the coating system.

Base-coat and clear-coat are applied in consecutive steps wet in wet (i.e. without intermediate curing) in what is usually called the top coat line. This term is very often also used for coloured coating material which is applied and hard cured as single layer without additional clear coat (generally for non-metallic paints.

Primer, base coat and clear coat are applied by spray processes, mostly with rotating atomisers with shape air and electrostatic charging of the paint droplets. Not all visible surfaces of a car body are coated with all of these layers. Usually each layer is applied in the following sequence: coating of interior surfaces (cabin, door openings, engine and boot compartment), followed by exterior surfaces. Manual coating is found in small paint shops or with low volume car bodies, and for interior coating.

Base coat

Base coats bring the color and the effect (metallic, pearly) to the car. They are applied on top of the primer layer and usually covered by the clear coat layer to promote a better appearance of the coat and to protect it from the environment. Usually 6 to 20 different colours are used in the base coat step, and low loss colour change techniques or colour batch coating are important measures to reduce paint and solvent consumption. Depending on the color, the required layer thickness may vary between 10 to 25 µm to account for different hiding powers of the colour pigments. The solids content and the VOC content may vary for the same reasons.

Three main base coat systems exist in paint shops of the automotive industry:

- Solvent based medium solids (MS), VOC content 80 +/-3 %
- Solvent based high Solids (HS), VOC content 60 % +/- 6 %
- Waterborne, VOC content 15 +/- 3 %

In a typical paint shop layout, the car body enters the top coat line via an air lock with dust removal systems followed by base coat application to the internal areas, either by manual or robot application, which is then followed by the external ESTA (Electrostatic) bell application. For solid colors, the full film build is applied in this step, while for effect colors a second base coat layer is applied wet in wet without electrostatic application.

In most cases the base coat is dried in an intermediate dryer (flash-off zone, 2-8 min at 50-60 °C, for partial evaporation of water and organic solvents, raising the solids content above 90%) and the body is conveyed to the clear coat zone.

If, depending on the product requirements, a final clear coat is not needed, the top coat is cured in the top coat dryer (typically 20- 30 min at 140 °C)

Clear coat

The clear coat is the topmost sealing layer and provides for high lustre and colour depth, optimum appearance, chemical and scratch resistance. The dry film thickness varies between 35 to 50 µm

- SBCC1 = 1K solventborne clear coat (all types) (1K = one-component paint), VOC content 42 +/- 3 %
- SBCC2 = 2K solventborne clear coat PUR (2K = two-component paint), VOC content 40 +/-5 %

In Europe waterbased clear coats or powder clearcoats are not used for coating of passenger cars.

Reworking: Repair of small localised top coat blemishes

The work processes and their environmental impact are detailed in standard VDI 3456. Compared to the overall series painting process, the environmental impact is low.

Materials used for these type of repairs are either paint repair systems (compliant with or the same / similar paints as in the main line. Bodies with larger defects are sanded and (eventually after masking the good parts) the whole body is put back into the top coat line (2^{nd} run)

For small surfaces, baking with IR heaters is to pre preferred over hot-air drying.

Cavity preservation (CP)

The corrosion protecting measures are finalized with the sealing of the cavities with wax materials. For this, two procedures are usually followed – spraying and flooding. For spraying, special nozzles are inserted in the cavities, and an exactly measured quantity of material is sprayed inside each cavity. For flooding, the cavities are filled with flooding wax, under pressure.

For the application of the wax, two automation procedures are used. The procedure that is clearly more flexible with regard to the position of the bores, is based on the introduction of the nozzles by robots. Here, several pneumatically fold-out nozzles are arranged in a nozzle-exchange head. The robot retrieves the required nozzle-exchange head from a magazine, applies it to the corresponding cavities and replaces it, to seize the next nozzle-exchange head. In the other automation procedure, numerous nozzles are arranged in a frame. After the car body is positioned above the nozzle plate, the plate is lifted, and all the nozzles are inserted simultaneously into the corresponding bores in the vehicle underbody and applied. With this procedure, many cavities can be sealed within a short cycle of time, provided the cavities are reachable.

VOC emissions are only produced if using solvent-based spray wax (about 0,25 kg/car body to 0,40 kg/car body, corresponding to about 3,0 g/m² to 4,7 g/m²). Modern plants apply mainly solvent free anticorrosive agents in spray or flood processes, which mean that no emissions are produced with the exception of small quantities of wax aerosols released during spraying.

Annex 3 - Adaptation of temporal and currency differences

In order to write this Annex, bibliographic references [2] listed chapter 11 were used.

Adaptation of currency differences

Currency conversion to EURO from literature values in foreign currencies are done, if available at the reported conversion rates and stated explicitly. If no currency conversion rate was given, the yearly average of the conversion rate was determined and used for calculation.

Adaptation of temporal differences

Due to the time value of money, investment and costs cannot be compared without integrating the temporal aspect. To enable the comparison of costs or investments from different years, various indexes have been developed. One of these indexes, the Chemical Engineering Plant Cost Index (composite CEPCI)[6] shall be used in this document to allow for temporal adjustments (see Table A1). The document works on EUR 2010.

Table A1: cost elevation factors derived from CEPCI (www.che.com)

Year	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Multiple	1.00	1.06	0.96	1.05	1.10	1.18	1.24	1.37	1.39	1.40	1.40

Utility costs

Table A2 displays the default utility costs used for calculating the operating costs of the pollutant abatement techniques. Country specific costs can be used otherwise.

Table A2: default utility costs

Utility	Price	Unit
Electricity	30	€/MWh

[6] Published by Chemical Engineering Journal, www.che.com.