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Environmental burdens of cataphoresis process

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ABSTRACT

The objective of this study is to appraise the environmental burdens of a cataphoresis process, most widely used surface coating operation in automotive sector. An industry having an annual production of around 6,100 trucks and busses is investigated by adopting life cycle assessment methodology. This study is a pioneering one performed with the actual data obtained from a Turkish automotive factory. The impact categories evaluated are climate change, acidification potential, particulate matter and respiratory inorganics, photochemical ozone formation, ecotoxicity freshwater potential, terrestrial eutrophication potential, freshwater eutrophication potential, marine eutrophication potential, human toxicity midpoint cancer effects, ozone depletion potential, and resource depletion (water). The total energy consumption of the cataphoresis process is approximately 12.5 kWh/m^2. Electrodeposition coating and the following ultrafiltration water rinse baths are the main sources of the environmental impacts. The contribution of transportation has insignificant effects on environmental impacts for all categories. Furthermore, energy consumption has substantial influence on almost all of the environmental impact categories. The results related to various energy scenarios conducted with wind, photovoltaic and hard coal instead of Turkish grid electricity indicate the usage of wind energy lowers all impacts.

Keywords: Automotive industry; Cataphoresis; Life cycle assessment; Environmental impacts; Energy source

1. Introduction

The automotive industry is one of the leading sectors on a global basis. Turkey is the 15th country in vehicle manufacturing in the world. The automotive industry has an important role in Turkish manufacturing sector. In 2017, more than 1 million vehicles are produced in Turkey [1]. Turkish automotive industry is the leading sector in the country in terms of the investments allocated for research and development [2].

Scientific literature on sustainability and innovation in the automotive sector is reviewed and in this perspective, the importance of issues such as cleaner production, life cycle assessment (LCA) studies, eco-innovation, reverse logistics are emphasized [3]. LCA can be used as a tool to support design for environment in automotive sector [4], due to its holistic approach. In terms of certain impact categories, such as climate change (CC), the main impacts arise due to use phase. However, production causes considerable amounts of certain environmental impacts as well. Supply chains associated in manufacturing generate the main share in freshwater ecotoxicity, mineral depletion and human toxicity [5]. As vehicles are manufactured by assembling diverse materials, LCA studies are performed on various parts of the vehicles (e.g. Exhaust valves, [6]), substitution of materials used for different parts [7,8], comparing lightweight materials with the others [9] in terms of environmental impacts. Besides, environmental burdens of conventional and electric vehicles are investigated based on

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their whole life cycles [5]. The reasons of getting different LCA results on electrical vehicles are analysed [10]. There are also studies performed on a part of production to aid the reduction of negative impacts.

Automotive production processes are basically divided into four as press, welding, surface coating (painting) and finally assembly. Surface coating (painting) operations are among the most important processes in the manufacturing train from both environmental concerns [11] and high quality requirements. The most polluting part of the vehicle manufacturing flow chart is surface coating (painting) where the aim is to obtain a clean substrate, free from contaminants such as oils, greases, waxes, corrosion products and other impurities. Besides, painting process is addressed as the most energy intense process in automotive manufacturing [12]. Painting is applied on metal and plastic parts in the automotive sector. Process of plastic part painting is different from metal painting [12].

In this respect, LCA methodology is adopted to develop strategies for the reduction of environmental impacts of surface coating [13]. Within diverse kind of metal coating methods, although cataphoresis process is identified as the best available technology, significant environmental impacts are generated from it.

The importance of site-specific data usage obtained from an actual plant in LCA studies must be emphasized especially for countries where scarce studies on quantifying the environmental impacts are found. Significance of research activities on LCA for such geographical areas is noted by Klopffer and Curran [14]. Since Turkey represents a good example of the countries with few studies on LCA [15–22], it is valuable to put forth trustworthy background data.

In this context, this study focuses on appraising the environmental burdens of the widely used cataphoresis process in a Turkish automotive industry by adopting LCA methodology. This study is the first of its kind conducted with the actual data obtained from a Turkish automotive factory.

2. Materials and methods

The automotive industry under investigation is located in Kocaeli on an area of 290,000 m^2. The factory having an annual production of around 6,100 vehicles composed of trucks and busses operates 5 d a week, employing 860 personnel. The environmental impacts arising from the cataphoresis process of the plant is explored by adopting LCA approach. Data is collected from the factory for about a year. GaBi 7.3 software is used for modelling and professional database used for background processes. Functional unit is defined as 1 m^2 of coated metal surface. Fig. 1 illustrates the system boundaries. The system is composed of 10 consequtive baths; all the inputs and outputs related to these baths are shown in the figure.

The environmental impact assessment is fulfilled by following the recommendations of the European Commission-Joint Research Centre, Institute for Environment and

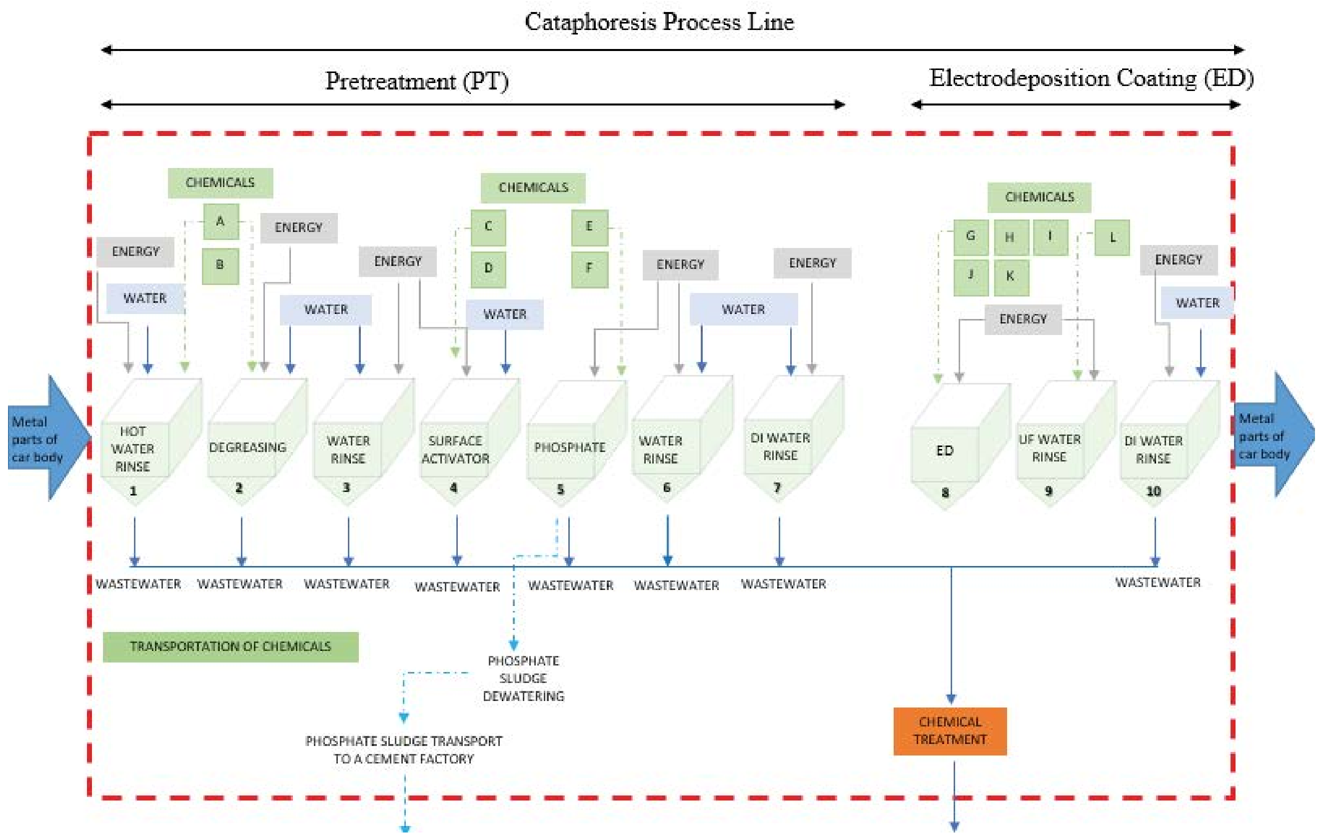

Fig. 1. System boundaries.

Sustainability [23]. The "ILCD/PEF recommendation v 1.09" method is selected to evaluate the environmental impacts. The impact categories considered are CC, acidification potential (AP), particulate matter and respiratory inorganics (PM), photochemical ozone formation (POF), ecotoxicity freshwater potential (EP), terrestrial eutrophication potential (ETP), freshwater eutrophication potential (EFP), marine eutrophication potential (EMP), human toxicity midpoint cancer effects (HT), ozone depletion potential (ODP), and resource depletion (water) (RD).

The database used does not contain electricity of Turkey. Therefore, a new process is established for electricity grid mix of Turkey based on Turkish electricity generation data [24]. The Electricity Generation Corporation of Turkey indicates that Turkish grid mix is composed of 32% natural gas, 22.1% hard coal and lignite, 36.4% hydro power, 7.6% wind. The share of solar energy together with geothermal, biomass, cogeneration and photovoltaic energies are totally 1.9% [24].

2.1. Production processes and inventory data

As seen from Fig. 1, cataphoresis process applied in the investigated facility is composed of 10 baths performed within two consecutive sub-processes of pretreatment (PT) and Electrodeposition (ED). During PT, the metal parts of the car body pass through the following baths; hot water rinse (Bath 1), degreasing (Bath 2), water rinse (Bath 3), surface activator (Bath 4), phosphate (Bath 5), water rinse (Bath 6), deionized (DI) water rinse (Bath 7). ED starts with a cataphoresis painting (also named as ED bath) (Bath 8), whereafter ultrafiltration (UF) water rinse (Bath 9) and DI water rinse (Bath 10) come. It should be noted that, in cataphoresis operations, semi-closed box profile of vehicle body transports the contents of previous bath to the next one. As a result a decrease in the volume of the baths is observed with time.

The first step in cataphoresis is hot water rinse (Bath 1) applied to remove the unwanted impurities from the metal surface that will be coated. Bath 1 having a volume of 100 m^3, is cleaned once a year. During cleaning, the content of the whole tank is discharged and the tank is refilled with DI water that has a conductivity of less than 2.5 μs. Bath 1 is conditioned with alkaline cleaners A and B. In order to provide efficiency this bath is heated to 50°C. Spray washing is applied to the vehicle body after it leaves Bath 1 to reclean the metal surface of car body and prepare this metal surface to the subsequent degreasing process. This spray technique is used in all baths to reduce the water consumption as recommended by Integrated Pollution Prevention and Control (IPPC) BREF document [25].

Degreasing (Bath 2) is second step of the PT, performed to remove oil from the metal surface by immersing it into alkaline hot water. Bath 2 has a volume of 100 m^3 and it is cleaned once a year. During cleaning operations, half of bath (50 m^3) which is the upper oily part, is discharged. After cleaning, 50 m^3 deionized water with less than 2.5 μs conductivity is added to the bath. Bath 2 is conditioned with alkaline cleaners A and B. The concentration of cleaners and retention time are adjusted according to the amount of oil on the metal surface. The temperature of the bath is set to 50°C. If sufficient cleaning of the surface is not ensured, the remaining oils and powders cause the phosphate x-tallisation on the surface. Spray washing is applied to the vehicle body after it leaves this bath.

To remove the oil remaining on the surface, the metal parts are dipped into water in Bath 3 that has a volume of 100 m^3. This tank is cleaned seven times a year. During the cleaning period, the content of the whole tank is discharged. After the cleaning, the bath is filled with DI water having less than 12 μs conductivity. Spray washing is applied to the metal at the end of this step.

Bath 4 is a surface preparation operation conducted by immersing the metal into a media that contains DI water and certain chemicals. The bath is cleaned twice a year by discharging all the contents (100 m^3). After cleaning, the bath is refilled with 100 m^3 of DI water with a conductivity less than 2.5 μs. This surface conditioning rinse is performed to refine crystal morphology and control the coating weight. Similar to other baths a spray washing is conducted to the pieces leaving the bath.

The next bath is zinc phosphating (Bath 5) that provides outstanding durability of painted parts in harsh environmental conditions. This process aims to give metal surface a better paint holding capability by coating the surface with a homogenous phosphate film and increasing the surface area of the metal. The temperature of the system is set to 48°C. Phosphate sludge is formed as a result of the reaction occurred during this operation. The system is equipped with a phosphate sludge filter press to separate sludge from the phosphate circulation fluid. Heat exchanger which is used to heat the phosphate fluid could be rapidly clogged as it is exposed to the phosphate sludge. To prevent the clogging, the heat exchanger is washed with nitric acid. The nitric acid washing is applied as a closed loop system where nitric acid is recirculated. Phosphating bath has a volume of 100 m^3 and it is cleaned once a year. During the cleaning, the content of the whole tank is sent to a filterpress and the filtered bath content is directed towards the bath again. Therefore no wastewater is generated from Bath 5. Spray washing is applied to the vehicle body after it leaves the bath in order to get rid of the residual phosphating chemicals. The dewatered phosphate sludge is sent to a cement factory.

Bath 6 is used to clean the surface from chemicals originating from the previous phosphate bath. Therefore this bath generates a wastewater with very high phosphate and metal ions content. The cleaning of this bath having a volume of 100 m^3, is of critical importance in achieving the required metal surface quality. Bath 6 is completely discharged and cleaned seven times a year. At the end of cleaning, the bath is filled with DI water with a conductivity less than 12 μs. Similar to other baths a spray washing is applied to the metal bodies leaving the bath.

The operations performed in Bath 7 aim to remove the residual ionic chemicals from the surface. Bath 7 is cleaned five times a year. During the cleaning, the content of the whole tank (100 m^3) is discharged. After each cleaning, DI water that has conductivity less than 2.5 μs, is used to fill Bath 7. At the end of the process a spray washing is conducted.

The vehicle body is immersed into Bath 8 where tension is applied to it. In the bath, the anode cells covered with semi-permeable jackets are placed on the sides and at the bottom of the tank. Cathode is the surface that will be coated. The required direct voltage is supplied by a rectifier unit (the correct tension transducer from the alternative voltage). Coating of the surface takes place under constant voltage (260 V) and variable current (600–180 A). As the film thickness increases, the surface conductivity under constant voltage decreases and therefore current passing through decreases. During coating, electrochemical reactions occur. This will cause positive ions formation within the paint. The removal of these ions from the medium is accomplished by semi-permeable anode membranes where the acetic acid solution is separately circulating (anolitic circulation system). Electrons (with negative charges) travel from the anodic cell in the membrane towards the cathode. While the positive ions move into the membranes. This will increase the conductivity of the anolyte liquid. However, the conductivity of anolyte liquid must be kept constant at 1200 mS. for this reason; DI water is fed to anolyte with an automatic valve. Paint, cationic resin, ethanol, isopropanol and acetic acid are the added chemicals to this bath. Cataphoresis paint is extremely settleable and requires continuous mixing. Circulation pumps are therefore operated on a continuous basis. Circulation is carried out through the use of bag filters with a pore size of 50 μ to ensure the dust and particles originating from the paint itself, as well as the external influences, are retained. As the cataphoresis coating is performed under direct electric current, heat is released during this process. This heat can deteriorate the paint. In order to avoid this, the dye circulation with a cooling unit is used to keep the paint at a constant temperature of 30°C. Effluent is not produced in Bath 8.

Vehicle parts are dipped into the Bath 9 to recover the excess paint remaining on the surface after cataphoresis coating. By doing so, the required quality of paint operation is provided and the cost of painting is reduced. Recovery of paint is performed with an UF unit. This bath consists of an important part of the ED coating system. Wastewater is not generated in Bath 9.

Last step in cataphoresis process is conducted in Bath 10 where a rinsing takes place. The bath is cleaned once in a year by discharging the contents (100 m^3). After the cleaning procedure, DI water is fed to the bath.

Summary of water requirements and wastewater generation related to cathaphoresis process is presented in Table 1.

The amount of chemical inputs to the baths together with information on their transportation and background production processes chosen from the database are tabulated in Table 2. Professional database used for background processes.

Aggregated inventory data is given in Table 3.

Table 1
Water requirement and wastewater generation of cathaphoresis process baths

Bath number	Water requirement	Wastewater generation
	kg/m^2	
1	0.6×10^{-3}	0.4×10^{-3}
2	0.5×10^{-3}	0.3×10^{-3}
3	1.5×10^{-3}	1.4×10^{-3}
4	0.7×10^{-3}	0.6×10^{-3}
5	0.2×10^{-3}	0.01×10^{-3}
6	1.5×10^{-3}	1.4×10^{-3}
7	1.2×10^{-3}	1.0×10^{-3}
10	0.6×10^{-3}	0.4×10^{-3}
Total	6.6×10^{-3}	5.4×10^{-3}

3. Results and discussion

3.1. Energy consumption

The total energy consumption of the investigated cataphoresis process is approximately 12.5 kWh/m^2, a level significantly higher than given in literature as 2.7 kWh/m^2

Table 2
Information on the chemicals used in cataphoresis process

	Chemical	Type of transportation/country	Distance (km)	Selected process from database
A	Alkaline cleaner AR	Truck/Turkey	13	Coating Silicate, Sodium Hydroxide
B	Alkaline cleaner B	Truck/Turkey	13	Anilin (Phenyl Amine)
C	Additive	Ship/Belgium + Truck/Turkey	6,575 + 20	Potassium Chloride, Phosphate
D	Prepalene X	Ship/Belgium + Truck/Turkey	6,575 + 20	Phosphate
E	Toner	Truck/Turkey	13	Sodium Hydroxide
F	Replenisher	Truck/Turkey	13	Phosphoric Acid, Phosphate
G	Grey paste	Truck/Turkey	7	Paint system
H	Emulsion Enviroprime Low Cure	Truck/Italy	1,754	Epoxy resin
I	Butoxyethanol	Truck/Turkey	7	Ethanol
K	Phenoxy Propanol Additive	Truck/Spain	3,593	Isopropanol
L	Additive	Truck/Germany	2,325	Acetic acid
M	Additive Kathon	Truck/Turkey	7	Calcium Ammonium Nitrate

[13]. This difference is obtained due to not operating the cataphoresis system at its full capacity. The investigated plant only uses 32% of its capacity. However, the energy consumption of all the baths are constant and do not depend on the realized production level. When the system is operated at its full capacity, an energy consumption of 4 kWh/m^2 can be obtained. This level is slightly higher than the literature [13]. The reason of getting such a result might be due to the production of trucks and busses in the investigated facility, whereas the literature values are given for passenger cars [13].

The distribution of energy consumption between the baths is given in Fig. 2. Bath 8 has the highest electricity consumption with about 48.5% of the total. The reasons for this can be summarized as follows: To reach a specific film thickness on metal parts, a constant voltage of 260 must be provided in Bath 8. The vehicle metal parts are immersed into Bath 8 where the temperature is kept constant at 30°C. Besides a constant circulations of the dye must be provided to keep desired dye quality. Unlike the other baths, although the production takes place for 8 h/d, the temperature of the tank is kept at 30°C and constant stirring is applied for 24 h in order to avoid the degradation and possible precipitation of the dye.

Table 3
Aggregated inventory data

Data	Amount	Unit
Inputs		
Metal part of car body	1	m^2
Deionised water	6.63E-03	kg/m^2
Electricity (from grid mix)	1.25E + 01	kWh/m^2
Coating Silicate	7.30E-03	kg/m^2
Sodium Hydroxide	5.80E-02	kg/m^2
Anilin (Phenyl Amine)	1.04E-02	kg/m^2
Potassium Chloride	2.40E-03	kg/m^2
Phosphate	2.12E-02	kg/m^2
Phosphoric Acid	4.90E-03	kg/m^2
Paint	2.65E-02	kg/m^2
Epoxy Resin	1.06E-01	kg/m^2
Ethanol	2.40E-03	kg/m^2
Isopropanol	1.50E-03	kg/m^2
Acetic acid	8.00E-04	kg/m^2
Calcium Amonium Nitrate	2.00E-03	kg/m^2
Calcium hydroxide	6.17E-06	kg/m^2
Sodium chloride	3.09E-06	kg/m^2
Process steam from natural gas	1.54E-04	kWh/m^2
Transportation		
Transportation by truck	1.95E + 02	kgkm
Transportation by ship	5.91E + 01	kgkm
Outputs		
Metal part of car body	1	m^2
Treated Wastewater	5.40E-03	kg/m^2
Phosphate sludge	4.00E-03	kg/m^2

Bath 9 is the second highest (20.5% of the total) energy consuming point in the production due to paint recovery system. Furthermore, all the baths have spray nozzles to increase the efficiency of the operations. Baths 8 and 9 have higher number of spraying nozzles that elevate their energy requirement.

3.2. Environmental impacts

The environmental impacts obtained in this study together with literature data are tabulated in Table 4.

The values of this study are higher than the ones given in literature [13]. The differences are obtained mostly because of the high energy usage of the factory in this study. The reasons to get such a result are discussed previously under energy consumption part.

The results on the contribution of various baths of the investigated production process to environmental impact categories are given in Fig. 3.

As evident from Fig. 3, Bath 8 where actual painting process takes place, has the highest share in all the investigated environmental impact categories. Contributions of 53%, 53%, 59%, 53%, 76%, 54%, 69%, 57%, 57%, 53% and 73% of CC, PM, POF, AP, ODP, ETP, EFP, EMP, EP, RD and HT respectively, come from Bath 8. Major contributor to Bath 8 for CC, PM, POF, AP, ETP, EMP and RD is electricity consumption whereafter cationic resin comes. In contrast, cationic resin is the main reason of impacts arising from Bath 8 for HT, EP, EFP and ODP.

After Bath 8, Bath 9 is accounted as the second contributor to CC, PM, POF, AP, ETP, EFP, EMP and RD categories. Bath 5 (phosphate bath) has the second share in ODP after Bath 8. On the other hand, besides Bath 8, Bath 1 and Bath 2 also contribute to EP due to silicate coating.

Fig. 4 presents the contribution of electricity, chemical inputs, transportation etc. to environmental impact categories.

The impact profile given in Fig. 3 shows that 74% of the total CC is arising from electricity consumption, after that

Table 4
Environmental impact assessment of Cataphoresis process

Environmental impact	Unit	This study	[13]
CC	kg CO_2-eq	6.92E + 00	1.09E + 00
PM	kg PM2.5-eq	3.57E-04	1.19E-04
POF	kg NMVOC	7.53E-03	4.05E-03
AP	Mole of H^+ eq	8.88E-03	2.10E-03
ODP	kg CFC-11 eq	2.59E-12	NAD
ETP	Mole of N eq	2.67E-02	NAD
EFP	kg P eq	1.34E-05	NAD
EMP	kg N eq	2.57E-03	NAD
EP	CTUe	1.56E-01	NAD
RD	m^3 eq	1.86E-01	NAD
HT	CTUh	7.19E-09	NAD

NAD: no data available

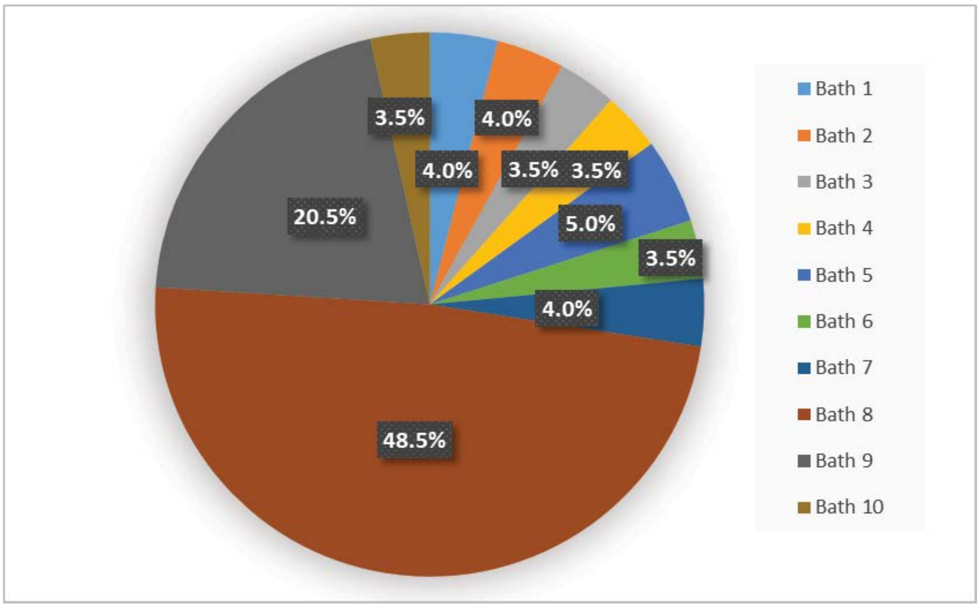

Fig. 2. Distribution of electricity consumption in cataphoresis process.

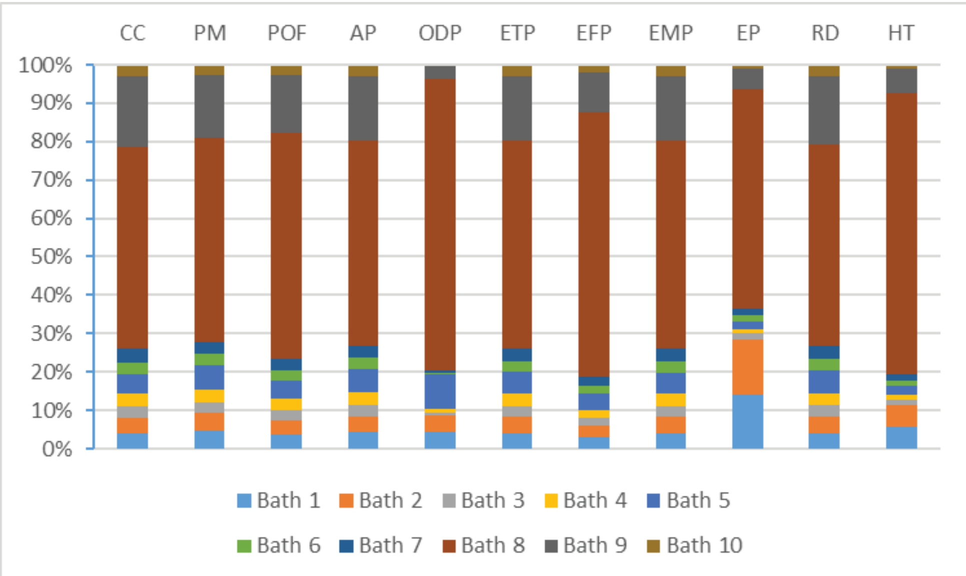

Fig. 3. Contribution of various baths to environmental impact categories.

cationic resin comes with 14% contribution. Similarly, electricity usage and cationic resin have 45% and 16% shares on PM, respectively. Rivera and Reyes-Carrillo [13], also indicated that the main contribution to CC and PM during painting is of electricity consumption. Besides, CC arises due to production of electro material [13]. Electricity consumption, cationic resin and pigment contribute 56%, 15% and 9% of the POF, respectively. AP is mostly generated due to electricity and cationic resin having 58% and 14% contributions, namely. The major factors constituting ODP can be given as; cationic resin (with 31% contribution to total ODP), electricity consumption (20%), sodium hydroxide (18%) and coating silicate (13%). Electricity requirement together with cationic resin contribute 62% and 17% to the total ETP. Around 43%, 34% and 14% of the total EFP is of electricity, cationic resin and sodium hydroxide origin, respectively. Total EMP is generated mainly due to electricity (64%), cationic resin (17%) and sodium hydroxide (11%). Coating silicate with 31%, cationic resin with 30%, electricity with 15% and wastewater with 14% contributions are the main reasons of EP. Approximately 42% and 40% of RD is arising from wastewater and electricity requirement. Finally, the major factors contributing to HT can be listed as cationic resin (with 33% input to total), electricity (26%), coating silicate (19%) and aniline (12%). Transportation has insignificant contribution (less than or equal to 1% of the total) on impact categories of

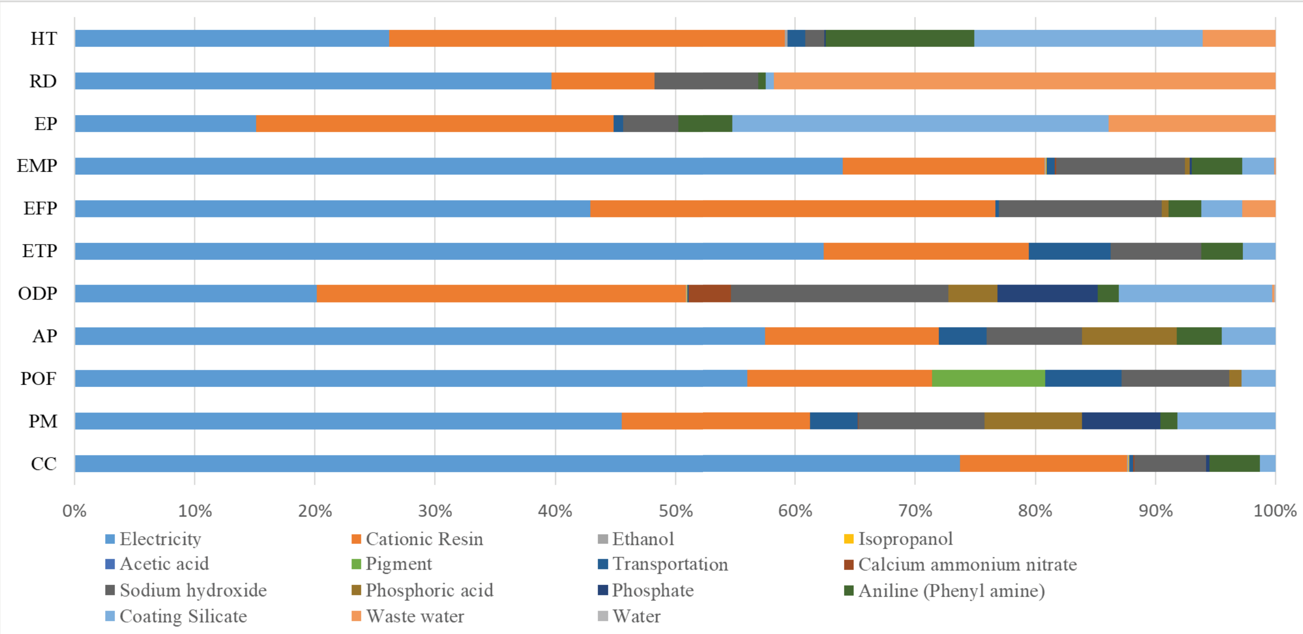

Fig. 4. Contribution of various factors to environmental impact categories.

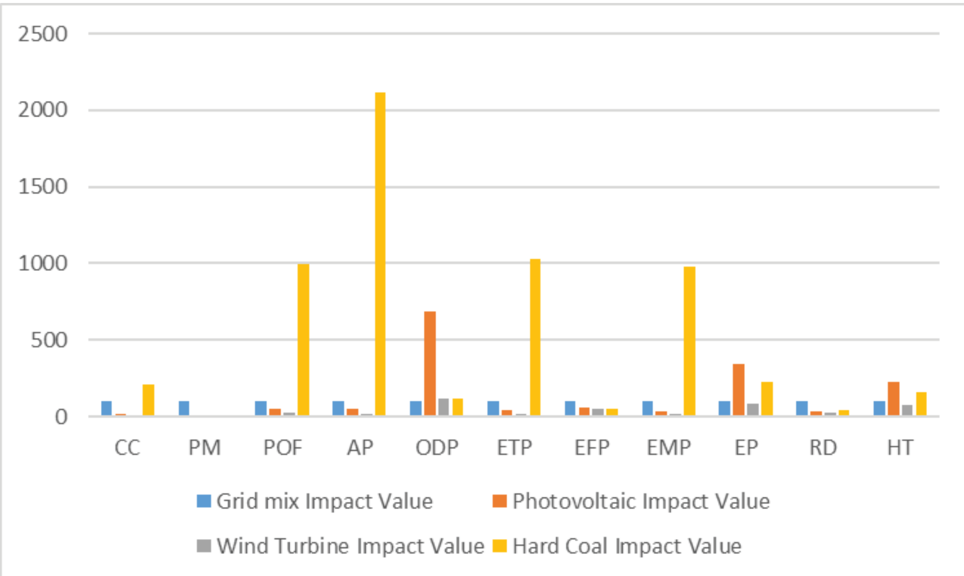

Fig. 5. Relative impacts of different energy sources compared to grid mix.

CC, ODP, EFP, EMP, EP and HT. On the other hand, contributions ranging from 4% to 7% are obtained on PM, POF, AP and ETP for transportation.

3.3. Sensitivity analysis on various energy sources

According to the above mentioned discussion on the origins of environmental impacts, it is evident that the electricity consumption is either the major contributor or among the significant contributors to environmental impact categories. Therefore, the source of energy to generate the electricity is defined as the hot spot of the study. For this purpose, alternative electricity sources of hard coal, wind turbines and photovoltaic energy are evaluated in comparison with the grid mix. The relative impacts of these energy sources are illustrated in Fig. 5.

Apart from EFP, ODP, and EMP, elevations on impact categories are observed due to the usage of hard coal as the energy source instead of grid mix. In case of using hard coal, an ODP value lower than grid mix, wind and photovoltaic energy is obtained. Usage of photovoltaic energy instead of grid mix results in lower levels of impacts for all the categories except HT. This finding is in accordance with another study performed on a water treatment plant [22], that indicates the usage of materials such as silicon (Si), cadmium (Cd) and copper (Cu) in the manufacturing of the photovoltaic cells yields elevated HT for this energy alternative. The usage of wind turbines in place of grid mix results in substantial reductions on all the investigated impact categories.

4. Conclusions

The total electricity consumption of the investigated surface coating process is approximately 12.5 kWh/m^2. The energy consumption of the process is constant and do not depend on the realized production level that is currently only 32% of the total capacity. Therefore, it is recommended to operate the process at its full capacity to achieve substantial energy savings.

Besides, almost all the environmental impacts are mainly generated due to electricity requirement of the process. Hence, the source of energy to produce the electricity is identified as the hot spot of this study. Hard coal usage in place of grid mix elevates all the environmental impacts apart from ODP, EFP and EMP. In case of getting energy only from photovoltaic cells rather than grid mix, the environmental impacts except HT are reduced. Usage of wind turbines instead of grid mix, is observed to improve considerably all the environmental impacts. Therefore, wind turbines are quoted as the most environmentally friendly energy alternative for this process.

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