Progress in Organic Coatings 186 (2024) 107998

Contents lists available at ScienceDirect

Progress in Organic Coatings

journal homepage: www.elsevier.com/locate/porgcoat

Sustainability of corrosion protection for offshore wind turbine towers

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ARTICLE INFO

Keywords:
Protective coatings
Offshore wind turbine tower
Quantitative sustainability
Life cycle assessment
Sustainable development
Corrosion Protection

ABSTRACT

When coatings industries have ambitions to develop more sustainable products it is important to know what path to follow. Quantitative evaluations in the form of Life Cycle Assessment (LCA) offers guidance for sustainability directions. The direction will depend on the type of coating. This work analyses sustainability performance of protective coatings, using the coating of an offshore wind turbine tower as a case. All steps in the manufacturing are assessed and the relevant environmental impacts are evaluated along the life cycle of the turbine tower. The assessment shows that the vast majority of the impacts, including climate change, originate from manufacturing of the steel. Therefore the durability of the coating system to protect the steel and prolong the lifetime, minimizing the need for repair, etc. should be the main priority for a sustainable direction. The coating system must keep the steel structures corrosion free for at least as long as the designed lifetime, as it is much more costly in terms of environmental impacts to repair or replace steel than to protect it properly from the start. When the protection is secured, the sustainable development path from the present situation where thermal sprayed metal (TSM) is used for galvanic protection of the wind turbine tower, will be to develop:

- Coating systems where toxic substances are substituted by less toxic or non-toxic substances.
- Coating systems where the thermal sprayed metal (TSM) layer is substituted by zinc-rich epoxy or Zinc silicate coatings.
- Coating systems where the organic solvents are substituted by water.
- Coating systems which would make it possible to reduce the amount of steel used.
- Coating systems where the organic binder material is substituted with alternatives with lower carbon footprint
- Ease of recycling the structure material for reuse in new structures.

1. Background

The coatings industry divides into segments or categories according to the main sector it contributes to, and the kind of coatings used. The steel construction industry building large structures like bridges, wind turbine towers, tank farms etc. use coatings belonging to the segment “protective coatings” [1]. For this segment, as the name implies, the main purpose for the coating systems is to protect the assets primarily against degradation and decomposition.

The majority of the coating systems in the segment are for protection of steel structures against corrosion. When the protection, and thereby the lifetime of the structure is ensured by selecting of a proper coating system, other purposes or functionalities like aesthetics, identification, high or low friction, just to mention some examples can be included into the coating systems.

The coating formulas used for larger steel structures are developed using materials selected in order to provide highest possible durability (longest lifetime) in the environment to which the assets (steel constructions) are exposed. Here, limitations are set by local legislation on chemicals and emissions to the local environment. The specification selection criteria are based on Standards that build on practical experience. Examples of widely used standards are either international like the ISO12944 [2], national such as NORSOK [3] or standards from companies like SHELL or Chevron. It is common that a number of

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https://doi.org/10.1016/j.porgcoat.2023.107998
Received 26 January 2023; Received in revised form 4 September 2023; Accepted 24 September 2023

performance criteria must be met, in order to qualify a coating system against a given standard.

In recent years when environmental sustainability has become a major focus point to reduce climate change and environmental deterioration, the Protective Coatings Industry also has a wish to contribute to a safe and sustainable future [4]. It is therefore relevant to investigate whether the described development path for protective coatings, based on coating standards and specifications developed by industry experts and companies, is compatible with environmental sustainability requirements, or whether we have to look in other directions for a more sustainable future for the protective coatings industry?

To address this inquiry, this study takes coatings of an offshore wind turbine tower as a case in point.

2. Method

The sustainability performance of a coating system is evaluated using life cycle assessment from cradle to grave. This covers all processes involved for both the coating and the substrate to which it is applied. A generic flow chart for the product life cycle is shown in Fig. 1. The model is applicable to all kinds of coatings, and in this paper, we have used it on an offshore wind turbine tower above the sea level, hence an example of a steel structure coated with a system from the "protective coatings" segment.

2.1. *Case: wind turbine tower*

The wind turbine tower is a steel tubular tower coated with various protective coating systems meeting the ISO 12944 standard (CX, very high durability) [5]. All the selected coating systems fulfill the requirements for corrosion protection of an offshore wind turbine tower above sea level.

2.1.1. *Steel tower*

The steel tower of a wind turbine is the main structure carrying the burden of the nacelle, rotor and the blades. It is made of mild steel plates in various thickness (typically 16–45 mm, average thickness estimated to 30 mm). The mild steel plates are bended, cut and welded to form the concave shape of the steel tower [6]. The required welding is estimated to be 0.6 m pr. square meter steel surface and the steel density is estimated to be 7870 kg/m^3.

2.1.2. *Surface preparation*

The steel tower needs surface preparation before application of the coating. This includes degreasing followed by abrasive blasting to the cleaning degree of Sa 3 and a roughness of minimum Rz 60–100 μm [7]. The abrasive blasting is performed using a blasting machine and blasting media (corundum: α-Al2O3, 50 Kg to prepare 1 m^2 [8]) sufficient to create the specified roughness.

2.1.3. *Coating systems*

All coating recipes used in this work are obtained from The Hempel Foundation Coatings Science and Technology Centre (CoaST) at the Technical University of Denmark. The coating recipes are considered to be average industry standard for the types of coatings used.

The choice of coating system for a wind turbine tower depends very much on experience of the designers. A coating system consist of typically three layers. A first layer of galvanic protective thermal sprayed metal followed by an epoxy intermediate and a polyurethane topcoat has for many years been used in the Danish wind turbine offshore market and has become the most commonly used system for the non-immersed areas above the splash-zone [9]. Alternative systems where Zinc-silicate or zinc-epoxy are used instead of the thermal sprayed zinc have a long track record from the offshore oil industry and both types are valid alternatives. Other alternative systems based on epoxy without galvanic corrosion protective primer have been used in a smaller scale, and all the coating systems mentioned are available in solvent and water-based version.

Details about the various coatings system are described in the ISO standard series ISO12944 [2], and all the coating specifications selected

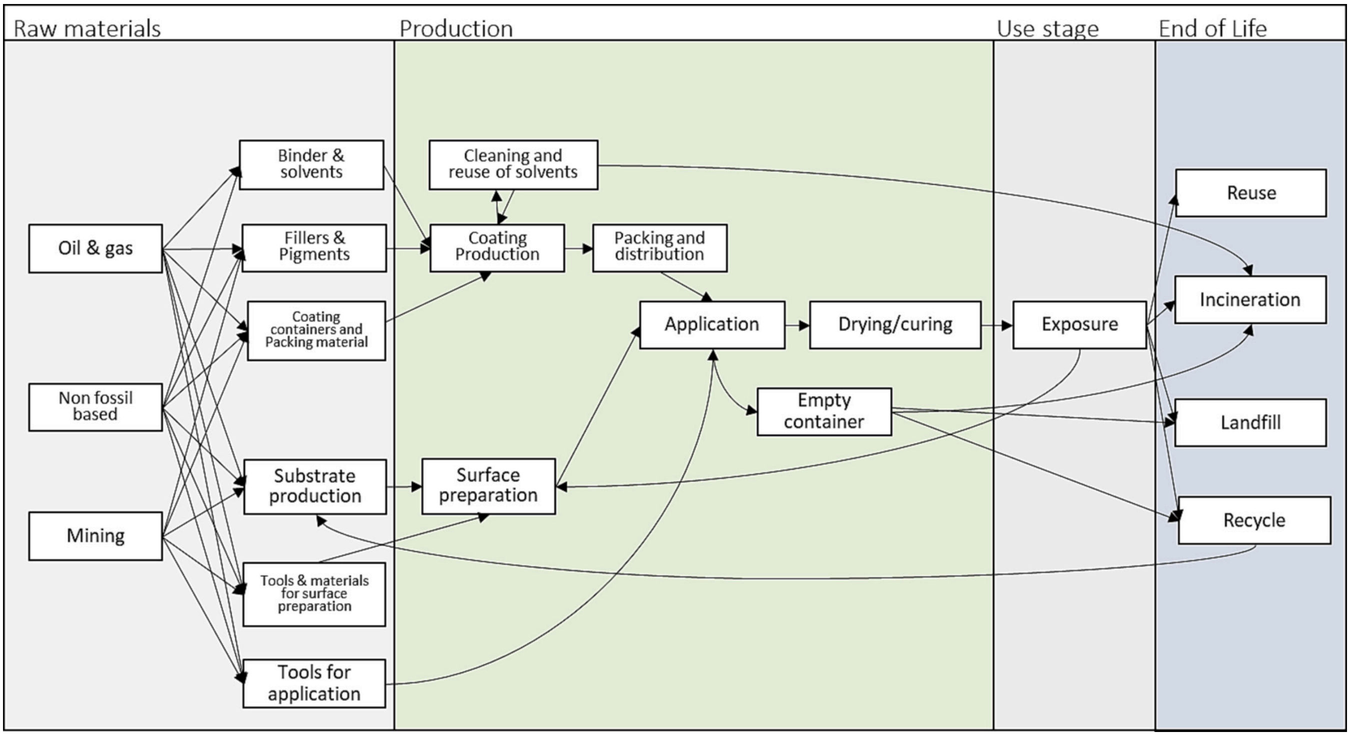

Fig. 1. A generic flow chart for life cycle model for the coating system including all processes in the 4 stages, (Raw materials, Production, Use stage and End of life), from cradle to grave. Each box represents a process or a collection of processes fulfilling a specific function.

in this work are drawn from the same ISO standard.

The selected basis coating specification in this work is a duplex system. It has been suggested as an industry standard, and consists of a thermal sprayed metal (TSM) 85/15 % zinc/aluminum as first layer in 60 μm thickness, an epoxy intermediate coating in 250 μm thickness and a polyurethane topcoat in 70 μm [10]. The first layer provides cathodic corrosion protection, the second layer a barrier protection and the final layer serves to add additional barrier protection, color and UV-resistance to the system. The alternative coating systems investigated in this work all have specifications that qualify them for use on an offshore wind turbine tower and can be assumed to protect the steel towers for the designed life time of 20 years without need for maintenance. Maintenance will be required only if the coating systems are damaged due to mechanical impact.

In the alternative coating systems the TSM layer is substituted with either a Zinc Epoxy layer or a Zinc Silicate layer. In both cases there is an option for a solvent based or water based system, resulting in four alternatives to the base case as shown in Table 1. For the two systems containing Zinc Epoxy the film thickness of the epoxy intermediate coating is increased by 50 μm to level out the corrosion protection level for the alternative systems [10].

2.1.4. *Coating application*

The application of the wet protective coatings (the epoxy and polyurethane layers) on wind turbine towers is in most cases done by use of airless spray in spray cabins. Heating is used to assist the drying and curing processes. In contrast the TSM layer is applied by use of a Thermal Spray technology, in this case an electric arc process is selected as this is the method with the fastest deposition rate [11].

2.2. *LCA*

The life cycle assessment proceeds through three phases that are described below - definition of goal and scope for the study, generation of an inventory of emissions and resource uses throughout the life cycle are described in the rest of Section 2, while the results of the environmental impact assessment of these flows between the production system and its surroundings are presented and discussed in Section 3.

Table 1
Specification of base case and alternative coatings for a wind turbine steel tower. Category CX very high durability [5]. All selected systems are qualified for use on a wind turbine tower.

Alternative coating specifications for a wind turbine tower (non-immersed areas above the splash zone)		
Base case:		
Thermal sprayed metal	60	μm
Solvent based Epoxy	250	μm
Solvent based Polyurethane	70	μm
	380	μm
Alternative (Zinc Epoxy, solvent based):		
Solvent based Zinc Epoxy	60	μm
Solvent based Epoxy	300	μm
Solvent based Polyurethane	70	μm
	430	μm
Alternative (Zinc Silicate, solvent based):		
Solvent based Zinc Silicate	60	μm
Solvent based Epoxy	250	μm
Solvent based Polyurethane	70	μm
	380	μm
Alternative (Zinc Epoxy, water based):		
Water based Zinc Epoxy	60	μm
Water based Epoxy	300	μm
Water based Polyurethane	70	μm
	430	μm
Alternative (Zinc Silicate, water based):		
Water based Zinc silicate	60	μm
Water based Epoxy	250	μm
Water based Polyurethane	70	μm
	380	μm

2.2.1. *Goal and scope*

In the open literature there are hundreds of Life cycle Assessments (LCA) covering wind turbines in every size from almost every country around the world. The environmental impacts are in almost all the cases assessed per unit energy produced by a wind turbine, [12–14], [15], allowing wind turbines to be compared directly with each other, and with other electricity producing methods based on their functional output.

In most published wind turbine LCAs the modelling of the applied coating systems is based on average datasets from life cycle inventory databases like Ecoinvent or GABI with no attention to the specific coating type. This is because the direct environmental impacts of the applied coatings are considered to be of low significance compared to the impact of the steel used for manufacturing the tower. This has resulted in a rather marginal focus on the coating system when evaluating the sustainability of a wind turbine [16]. Consequently, there seems to be no pressure from the wind turbine owners and operators to make any changes in regards to the existing coating systems.

By evaluating the environmental impact from the wind turbine tower with focus on the coated steel, we will be able to establish the influence of the coating system on the impacts from the total wind turbine tower. This will allow us to guide the direction of the development of “protective coatings”, in order for both the coatings industry and their customers to become more sustainable.

To determine which factors influence the environmental sustainability of protective coatings applied to steel wind turbine towers, we have performed a LCA to quantify the environmental impacts from the whole system. This includes all processes involved in manufacturing of the substrate and the coating, the application processes, the transportations, the end of life treatment, and other relevant processes from cradle to grave. Fig. 1 shows the generic flow and processes involved. Each box represents a process or a combination of processes that together performs the desired operation, and by comparing impacts from these processes, it will be possible to identify the “hot spots” as areas for future actions to improve the sustainability.

The LCA is performed according to the ISO14040 [17] and ISO 14044 standards [18]. The functional unit is 1 m^2 offshore wind turbine tower coated to ensure protection in accordance with the standard ISO 19244-5 [5] for 20 years, (20 years is the standard design lifetime for a wind turbine used in most LCA works) [16].

2.3. *Life cycle inventory analysis*

2.3.1. *Attributional LCI modelling framework*

Since this work is performed to find a sustainable direction for the development of the protective coatings industry, no major changes in the background system is expected to take place as a result of this work. According to the ILCD guideline [19], the LCI Modelling Framework should thus be attributional. In accordance with the ISO standards for LCA, the ILCD also recommends using average processes for the modelling of the background system and multifunctional processes to be handled by system expansion with marginal processes when subdivision is not possible and allocation when system expansion is not possible.

2.3.2. *System boundaries*

The product system comprises all the processes that are involved in allowing the functional unit to be delivered – from cradle to grave. It is divided into foreground and background systems that are defined by boundaries as shown in Fig. 2. The foreground system represents the processes under control of the coatings manufacturer and immediate suppliers, and specific inventory data in direct relation to the coatings and the coatings processes are available here. The background system represents all other processes involved in the life cycle.

The basis of the life cycle inventory modelling is a description of

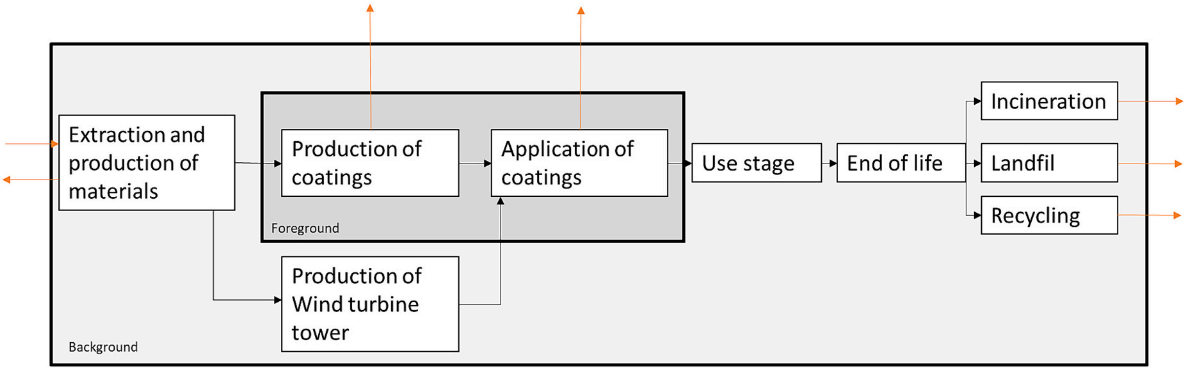

Fig. 2. The system boundaries - Inventory data for the foreground system are obtained from CoaST Laboratory at DTU as well as the CEPE database on chemicals used in the coatings industry [20]. Background data are data from available literature and the ecoinvent 3.8 database [21].

every process involved in terms of its inflow and outflow of materials, energy and chemicals. The processes involved are linked together to make it possible to follow the flows throughout the whole life cycle from cradle to grave.

2.3.3. *Inventory data*

The data used for modelling the foreground processes are obtained from the CEPE database on raw-materials used in the coatings industry [22], and detailed data on coatings formulations from the CoaST Laboratory at the Technical University of Denmark (DTU). Table 2 shows the generic type of raw materials required to model 1 kg of epoxy intermediate coating.

For surface preparation and application, average data are used based on assumptions of the most likely used technology [8,23]. Data for modelling the background processes like energy system and transportation are taken from the latest Ecoinvent 3.8 database as well as data available from various literature. The CEPE database is considered of high quality and is developed to be used for calculating the following flows and environmental impact category scores [20]:

- Resource use
- Water use
- Emissions to air
- Emissions to water
- Waste
- Global warming potential
- Acidification potential
- Eutrophication potential
- Human toxicity potential
- Photochemical ozone creation potential

2.3.4. *LCA methodology*

The OpenLCA software is used to model the inventory flows and calculate the environmental impacts from the Life Cycle processes. The CEPE database does not fit in OpenLCA directly, but the elementary flows have been mapped with the existing flows in the OpenLCA software [24].

The ReCiPe 2016 [25], Midpoint (H) methodology is selected for calculations of the environmental impacts, as it is often used when performing assessments in the chemical industry and it utilizes the latest updated knowledge on the included impact categories [26]. The impact category ‘Land use’ is not included in this study, as the CEPE database does not provide the needed inventory information. This leaves 17 impact categories in total.

The impact categories can be divided into categories with global effects, regional effect and categories with mainly local effects. To the categories with global effect belong the global warming and the stratospheric ozone depletion as emissions to the air in these categories will have the same effect irrespective of where in the world the emission takes place. Other categories with global effect are the depletion of non-renewable resources. The impact categories with regional effects are acidification, eutrophication, ecotoxicity, and photochemical and particle air pollution. Whereas the remaining category, ‘depletion of water resources’ are considered to have local environmental effects only.

Table 2
Coating formula for the epoxy intermediate coat used as part of the input in the coating process.

Epoxy intermediate coating formula:	Amount	Unit
Solvent	0.290	kg
Epoxy resin	0.205	kg
Fillers, pigments and additives	0.230	kg
Amide curing agent	0.275	kg

2.3.5. *Assumptions*

In this work, it is assumed that the wind turbine tower when coated with an appropriate coating system (CX, Very high durability, ISO 12944-9) will have no need for maintenance during its lifetime [27]. This is a common assumption for the many LCAs performed on wind turbines. Furthermore, it is considered important to include the steel into the ‘product system’, in order to cover both the coating system and steel substrate. This is relevant when evaluating the environmental impacts, as the substrate and the expected lifetime are selection criteria for choosing the coating system.

3. Results

3.1. *Wind turbine tower*

The impact from the 1m^2 wind turbine tower coated with the basis system on the 17 selected impact categories from ReCiPe 2016, midpoint (H) is shown in Table 2. The relative contribution from the coatings is relatively low in all impact categories, being <5 % of the total, except for the category ‘Terrestrial ecotoxicity’ where the metallic zinc used in the thermal sprayed metal coat alone accounts for >6 % of the total impact in the category. The majority of the impacts from coatings application origin from the metal spraying process and are for most categories a little lower than impacts from the coatings with the exceptions of ‘freshwater and marine eutrophication’ and ‘ionizing radiation’. The impacts from the turbine tower (steel substrate) is dominant in all categories (Table 3).

3.2. *Environmental impacts from alternative coating systems*

Even though the steel tower without coating is the major source to environmental impacts in all categories analyzed, it is still interesting to

Table 3
Impact scores in 17 categories for 1m^2 coated wind turbine tower using the impact assessment method ReCiPe 2016, Midpoint (H). (1,4-DCB = 1,4-Dichlorobenzene).

Impact categories	Reference unit	Basis coating system (TSM)	Turbine tower	Coating application	Others (Packing, surface preparation transportation, end of life)	Total	Coating share of total
Global:							
Global warming	kg CO2 eq.	9.66E+00	4.96E+02	5.28E+00	1.01E+02	6.11E+02	1.6 %
Stratospheric ozone depletion	kg CFC11 eq.	1.04E-05	1.80E-04	2.95E-06	3.66E-05	2.30E-04	4.5 %
Fossil resource scarcity	kg oil eq.	2.53E+00	8.39E+01	8.79E-01	1.53E+01	1.03E+02	2.5 %
Mineral resource scarcity	kg Cu eq.	3.01E-01	3.78E+00	4.34E-03	4.28E+00	8.37E+00	3.6 %
Regional:							
Terrestrial acidification	kg SO2 eq.	4.45E-02	1.55E+00	2.18E-02	6.12E-01	2.23E+00	2.0 %
Freshwater eutrophication	kg P eq.	4.16E-03	2.49E-01	5.47E-03	4.53E-02	3.04E-01	1.4 %
Marine eutrophication	kg N eq.	3.60E-04	5.30E-02	3.60E-04	2.10E-03	5.58E-02	0.6 %
Freshwater ecotoxicity	kg 1,4-DCB eq.	6.16E-01	3.82E+01	2.93E-01	2.05E+01	5.97E+01	1.0 %
Marine ecotoxicity	kg 1,4-DCB eq.	1.02E+00	5.18E+01	3.84E-01	2.61E+01	7.93E+01	1.3 %
Terrestrial ecotoxicity	kg 1,4-DCB eq.	2.38E+02	2.16E+03	8.70E+00	5.11E+02	2.91E+03	8.2 %
Human carcinogenic toxicity	kg 1,4-DCB eq.	5.39E-01	9.55E+01	3.26E-01	6.26E+01	1.59E+02	0.3 %
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	4.00E+01	1.09E+03	7.85E+00	2.30E+02	1.37E+03	2.9 %
Ozone formation, Human health	kg NOx eq.	2.60E-02	9.77E-01	8.94E-03	3.38E-01	1.35E+00	1.9 %
Ozone formation, Terrestrial ecosystems	kg NOx eq.	2.65E-02	1.01E+00	9.63E-03	3.42E-01	1.38E+00	1.9 %
Fine particulate matter formation	kg PM2.5 eq.	1.73E-02	8.97E-01	7.71E-03	2.26E-01	1.15E+00	1.5 %
Ionizing radiation	kBq Co-60 eq.	2.43E-01	4.25E+01	8.99E-01	2.50E+00	4.62E+01	0.5 %
Local:							
Water consumption	m3	2.90E+01	2.67E+03	2.71E+01	2.06E+02	2.94E+03	1.0 %

see if an alternative zinc containing coating system could have positive or negative environmental effects. To evaluate this four alternative coating systems are compared in a new LCA to the base case coating system with TSM as primer coat followed by solvent borne epoxy/polyurethane. The alternatives comprise two solvent based systems where the TSM coat is replaced with Zinc epoxy and Zinc silicate respectively, and two similar water based systems. Details and film thicknesses are shown in Table 1.

The life cycle impact scores for the alternative coatings are calculated using the method described in Section 2, assuming that the production of the steel tower, as well as the surface preparation, the use stage and the end of life stage are the same for all five alternatives and can therefore be omitted from the comparative LCA calculations. The results thus show the contribution from the coatings and the application alone.

Table 4 shows the contributions from the base case TSM and four alternative coatings to the selected 17 environmental impact categories. The base case relying on TSM is the least attractive alternative in all categories. It is more difficult to conclude which system is the most attractive as the four alternative system have their advantages depending on the impact category. The impact result in the six categories, ‘terrestrial acidification’, ‘freshwater eutrophication’, ‘freshwater ecotoxicity’ ‘marine ecotoxcity’, ‘fine particulate matter formation’ and'human carcinogenic toxicity’ are close with <15 % difference between highest and lowest value.

The largest difference between four alternatives are in the categories of ‘stratospheric ozone depletion’ (73 %) and ‘marine eutrophication’ (62 %). For the ‘stratospheric ozone depletion’ it is the dinitrogen monoxide (N2O) and halogenated carbon gasses used in raw-material production that are responsible for the impacts and in the ‘marine eutrophication’ category it is the emissions of nitrates and ammonia from production of the raw materials which cause the differences.

For the “global warming” impact category, the water based systems seems to be the most attractive.

3.3. Normalized impact scores

It is a very clear conclusion that the basis system based on TSM is the least attractive system of the five alternatives, whereas it is not so clear which is the most attractive, as it depend on the impact categories evaluated. To support a comparison across impact categories, all impact scores are normalized against the annual impact from an average person to express them in the common unit a “person equivalent” (PE). Fig. 3 shows the normalized value for the five categories with direct reference to emission of toxic substances. It is clear that relative to this common background load, the highest contribution from the coating of 1 m^2 wind turbine tower is to ‘human carcogenic toxicity’ for all coating systems with a maximum value of 0.08 PE for the Thermal Sprayed system. The main contributor here is the emissions that originate in the production of the metal wires (zinc/aluminum) used in the Thermal Spraying process which alone account for 62 % of the total.

However, it is known, that the external normalization factors for categories related to toxicity have a much higher uncertainty compared to non-toxicity related category like global warming. This is because effects from emission of toxic materials are much more complex and uncertain compared to the effect for e.g. emission of greenhouse gasses [28].

Fig. 4 shows the normalized impact scores for the global categories and here the highest contributions are for the use of fossil resources with PE values up to 0.004. The emission of greenhouse gasses (the carbon footprint) is comparatively low but there is still a measurable contribution and it has to be remembered that the functional unit is just 1 m^2 of coated surface. The basis system with TMS is still the least attractive alternative and there is a tendency to conclude that the water based

Table 4
The LCA result from comparing five alternative coatings systems applied on a wind turbine steel tower. The green color represents the lowest value in a given category and the orange color represent the highest value.
(1,4-DCB = 1,4-Dichlorobenzene).

Impact Categories	Reference unit	Basis system TSM	Solvent based Zinc Epoxy	Water based Zinc Epoxy	Solvent based Zinc Silicate	Water based Zinc Silicate
Global:						
Global warming	kg CO2 eq.	1.49E+01	7.63E+00	6.60E+00	6.78E+00	5.51E+00
Stratospheric ozone depletion	kg CFC11 eq.	1.34E-05	1.15E-05	3.41E-06	9.23E-06	3.04E-06
Fossil resource scarcity	kg oil eq.	3.41E+00	2.57E+00	1.91E+00	2.30E+00	1.64E+00
Mineral resource scarcity	kg Cu eq.	3.05E-01	1.11E-01	1.54E-01	1.25E-01	1.37E-01
Regional:						
Terrestrial acidification	kg SO2 eq.	6.63E-02	2.86E-02	2.75E-02	2.90E-02	2.55E-02
Freshwater eutrophication	kg P eq.	9.63E-03	1.73E-03	1.94E-03	2.00E-03	1.89E-03
Marine eutrophication	kg N eq.	7.20E-04	2.30E-04	5.80E-04	2.20E-04	5.00E-04
Freshwater ecotoxicity	kg 1,4-DCB eq.	9.09E-01	2.35E-01	2.43E-01	2.71E-01	2.45E-01
Marine ecotoxicity	kg 1,4-DCB eq.	1.41E+00	3.77E-01	3.88E-01	4.36E-01	3.87E-01
Terrestrial ecotoxicity	kg 1,4-DCB eq.	2.46E+02	7.31E+01	7.13E+01	8.52E+01	7.03E+01
Human carcinogenic toxicity	kg 1,4-DCB eq.	8.64E-01	1.21E-01	1.25E-01	1.36E-01	1.27E-01
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	4.79E+01	1.52E+01	1.48E+01	1.77E+01	1.47E+01
Ozone formation, Human health	kg NOx eq.	3.50E-02	2.01E-02	2.48E-02	1.77E-02	2.17E-02
Ozone formation, Terrestrial ecosystems	kg NOx eq.	3.62E-02	2.26E-02	3.14E-02	1.91E-02	2.72E-02
Fine particulate matter formation	kg PM2.5 eq.	2.50E-02	9.99E-03	9.72E-03	1.03E-02	9.05E-03
Ionizing radiation	kBq Co-60 eq.	1.14E+00	2.13E-01	3.16E-01	2.41E-01	3.19E-01
Local:						
Water consumption	m^3	5.61E+01	3.17E+00	4.01E+00	3.00E+00	2.92E+00

alternatives are the most attractive alternatives for the global impact categories.

3.4. Global warming

In the following section, focus will be on the impact category 'Global Warming'. This category is selected due to its present importance in the global endeavors to limit global temperature increase to 2 °C (preferably below 1.5 °C) since the beginning of the industrial era as laid down in the Paris agreement [29], and because greenhouse gases have global consequences when emitted to air and distributed around the globe.

In the first assessment where we looked at the whole coating system including the steel tower we can from Table 5 see that the processes contributing the most to the emission of greenhouse gasses (the carbon footprint) are the ones leading up to manufacturing and application of the coating accounts for 2.5 % of the combined emission. The dominant processes accounting for the environmental impacts are the processes involved in the manufacturing of the steel tower where the most important factor is the steel that is used.

Concentrating on the global warming impact, we can from Fig. 5 see that replacing the basis coating system based on TMS with any one of the alternatives will result in a substantial reduction in CO2-equivalent emission. The maximum reduction of CO2-eq emission is obtained with the water based zinc silicate system where a 63 % reduction in emission is obtained.

For many wind turbine manufacturers and owners it is a very great step to change to water borne alternatives, but also the smaller step to solvent-based zinc rich epoxy will give a 48 % reduction in global warming emissions from the coating system.

The material contribution to the greenhouse gas emission for the alternative coating systems show that the largest contributor is the metal from the basis system (TSM) followed by the binder parts (Epoxy and Polyurethane) of the organic coatings. This indicates that future research in alternative binder materials with lower carbon footprint could be interesting to look into.

3.5. Sensitivity and uncertainty

In the results section above where the impact contribution from the coating system and the steel tower are evaluated respectively, it is important to see how sensitive the results are for the two parts. An analysis shows that a perturbation of 10 % in steel weight results in a normalized sensitivity coefficient between 0.74 and 0.96 for all impact categories and for a similar perturbation of 10 % for the coating system results in a normalized sensitivity coefficient between 0.01 and 0.12 for all categories. This supports the conclusion that the manufacturing of the steel is the most influencing process for al impact categories.

There are many sources to uncertainty when performing LCA for coatings and coating systems. The data for background processes are based on average data contained in the latest Ecoinvent 3.8 database, which is based on processes, that does not always contain the latest available technology. However the outcome of the LCA, is quite solid when it comes to the understanding about which part of the wind turbine tower contributes the most to the environmental impacts. These findings support the conclusions.

The selection of the ReCiPe 2016 methodology can also be questioned. Whether the ReCiPE 2016 (H) method corresponds to other methods, Global warming potential has been calculated using three different methods. The ReCiPe 2016 (H), the EF 3.0 and the CML-IA baseline. The calculated Global Warming potentials for the three

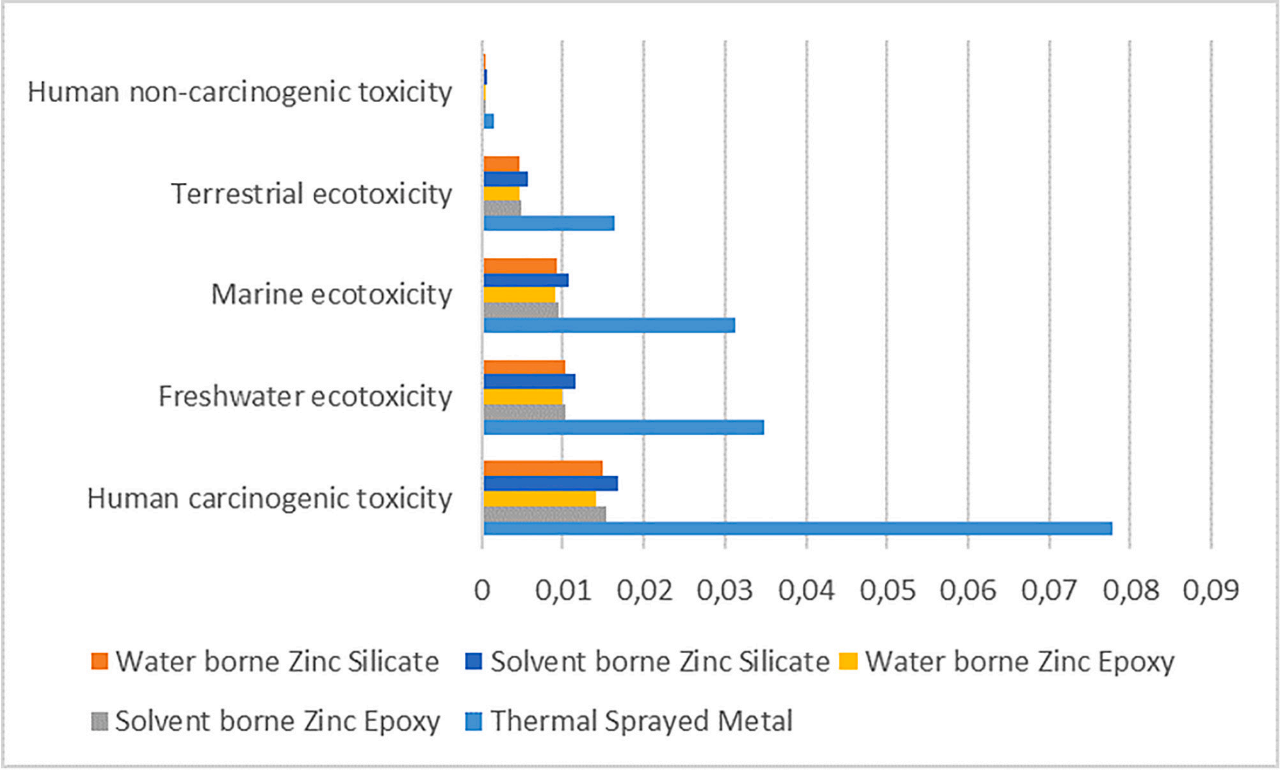

Fig. 3. Normalized values using ReCiPe2016(H)World(H) methodology for the impact categories with direct reference to emission of toxic substances. The unit is Person Equivalent (PE).

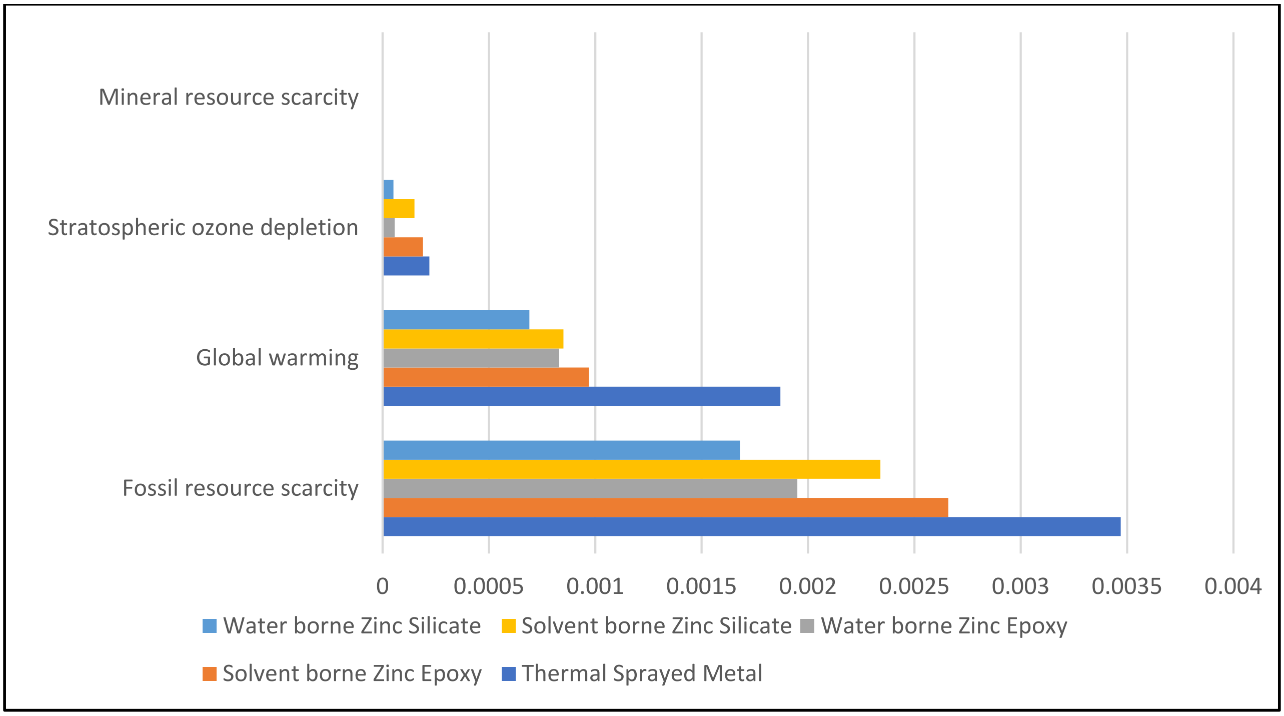

Fig. 4. Normalized values using ReCiPe2016(H)World(H) methodology for global impact categories. The unit is Person Equivalent (PE).

methods can be seen in Fig. 6 and the ReCiPe 2026(H) seems to give a good average between the different methods.

4. Discussion

4.1. Sustainability and coatings

Coatings are different depending on the purpose of use. First priority

Table 5
Process contribution to Global warming.

Contribution	Process	Amount	unit
100 %	1 m^2 wind turbine tower	611	Kg CO2-eq
81 %	Steel tower	496	Kg CO2-eq
16.5 %	Others	101	Kg CO2-eq
0.9 %	Application	5.3	Kg CO2-eq
1.6 %	Coating system	9.7	Kg CO2-eq

for coatings belonging to the segment 'Protective coatings' is to provide protection against deterioration and degradation to the substrate it is applied. Secondly it can provide color and other features. In such cases it is not relevant to look at the coatings alone if the sustainability is to be evaluated, as the impacts from the coatings have a much lower significance compared to the substrate/steel it has to protect. This supports the arguments that a sustainable direction for development within 'protective coating' is to provide protection for at least as long as the projected design life for the structure, to avoid recoating under non-optimized production conditions.

The results from the LCA (Table 2) show the impacts from the protective coating system used to protect the wind turbine tower in 17 different midpoint categories. It is clear that impacts originating from the coating system alone have a lower impact in all categories compared to the steel, but still contribute to the overall environmental impacts. Especially in the category 'terrestrial ecotoxicity' where the primer coating (TMS) with relative high zinc content, used to provide cathodic corrosion protection, is responsible for emission of toxic material to the environment and in the category 'mineral resource scarcity' where also again the use of zinc in TMS is responsible for the relative high use of mineral resources. A sustainable path for development within the protective coatings would consequently be to look for alternatives to zinc containing primers.

It is possible to find suitable 'metal free' coating systems, which fulfill the protection/durability requirements and hence are qualified to

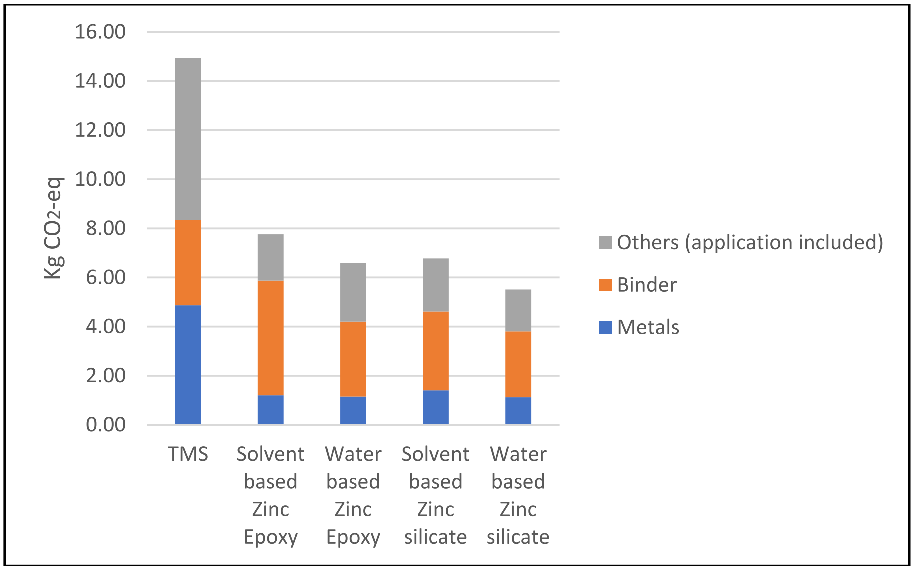

Fig. 5. The Global warming impacts from the basis system consisting of thermal sprayed metals (TSM) followed by solvent based (SB) epoxy/polyurethane coatings and four alternative coating systems.

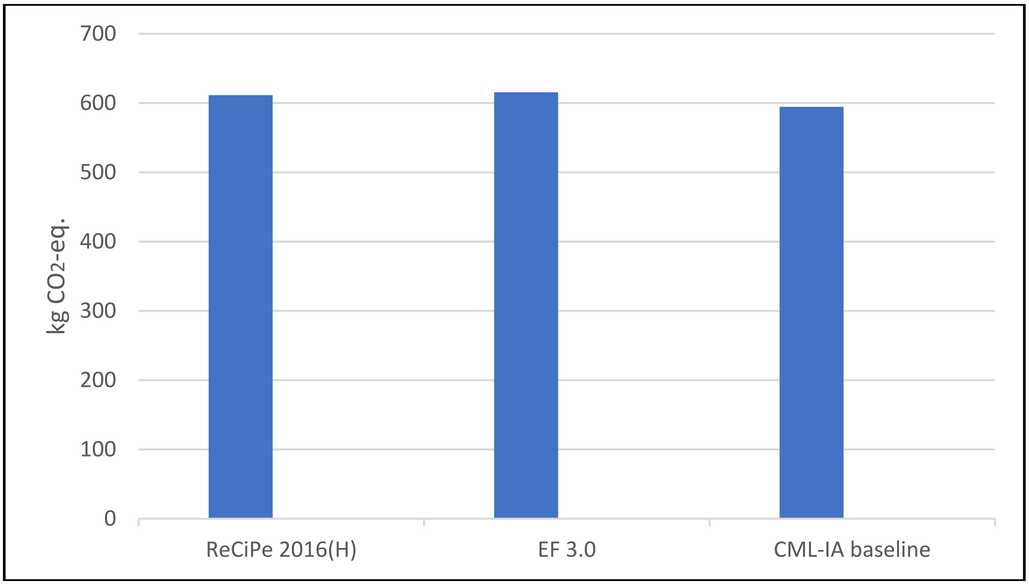

Fig. 6. Calculated Global Warming potential in kg CO2-eq from 1m^2 coated wind turbine tower using 3 alternative methodologies.

use on offshore wind turbine towers. Examples with pure epoxy systems exist, and a simple LCA calculation where the traditional basis TSM system is compared with a pure epoxy system show a considerable reduction (>90 %) in the impact categories 'mineral resource scarcity' and 'terrestrial ecotoxicity' as seen in Fig. 7.

Also in the category 'global warming', it is important not to ignore the impacts from the coating system, even though it is low compared to the impacts from the steel tower. In Fig. 7 it can be seen that the reduction in global warming emissions for the coating system is 38 % when changing from thermal sprayed metal (TSM) to an epoxy system without zinc.

It is probably not all wind turbine manufacturers or owners who would change to metal free coatings, as many still consider it a risk if no galvanic zinc containing coating is applied. It could be that they will accept an intermediate solution where, the TSM coating is substituted with either a Zinc silicate coating or a zinc rich epoxy coating.

There are several of possibilities of coating systems based on zinc silicate or zinc rich epoxy and for some it is even possible to find them in both solvent borne and water based alternatives and still a lot of research is performed to improve the zinc rich coating systems.

4.2. Other paths towards sustainability

Another way to reduce the environmental impacts from manufacturing of a wind turbine tower could be to evaluate if it is possible to reduce the amount of steel used to construct the tower.

A traditional way to design the steel thickness is to calculate the steel needed to give the strength and then add a corrosion allowance and some safety – enough to compensate the material loss at the offshore site for the designed lifetime of the tower in case the coating system breaks down for some reason. The classification companies in the maritime sector such as Lloyds register, ABS and similar recognize that certain coating systems shows sufficient durability and corrosive protection performance to be classified as "recognized corrosion allowance coatings" and by then accept a lower total steel thickness without compromising the structure and strength.

Utilizing LCA calculations cannot be employed to determine the safety parameters for the coating system or the wind turbine tower. However, it is feasible to assess the impact on environmental indicators by substituting 1 mm of steel with 1 mm of epoxy coating. This consideration can be integrated into the design process for both the steel tower's dimensions and the coating system (Fig. 8).

5. Conclusion

There are several paths to follow for the protective coatings industry in order to become more sustainable. By use of a suitable model, accurate data and LCA software it is possible to calculate the environmental impacts caused by the coatings and substrate and from the processes involved in the whole life cycle from cradle to grave and by then set the direction for future development.

- Coating systems, which will keep the steel structures corrosion free for as long as the designed lifetime as a minimum is of first priority, as it is much more costly in terms of environmental impacts to repair/replace steel than to protect it proper from start.
- Coating systems where toxic substances are substituted by less toxic or non-toxic substances.
- Coating systems where the organic solvents are substituted by water.
- Coating systems where the thermal sprayed metal (TSM) layer is substituted by zinc-rich epoxy or Zinc silicate coatings.
- Coating systems which would make it possible to reduce the amount of steel used.
- Coating systems where the organic binder material is substituted with alternatives with lower carbon footprint

CRediT authorship contribution statement

Mads Juhl: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Michael Z. Hauschild:** Conceptualization, Validation, Writing – review & editing, Supervision. **Kim Dam-Johansen:** Conceptualization, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

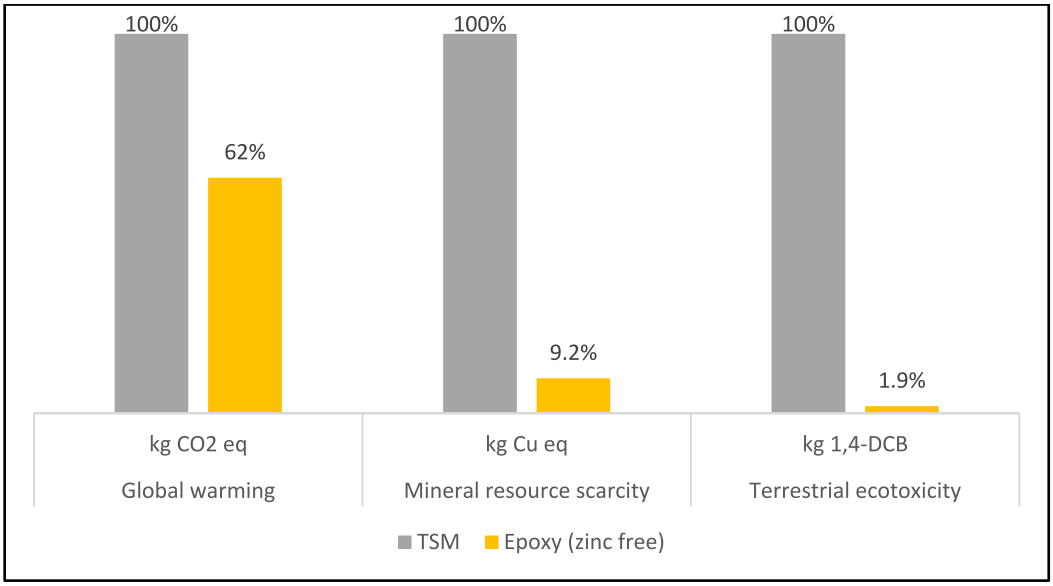

Fig. 7. Relative indicator results of the basis TSM coating system compared to the pure epoxy (zinc free) system. For each indicator, the maximum result is set to 100 % and the results of the other are displayed in relation to this result.

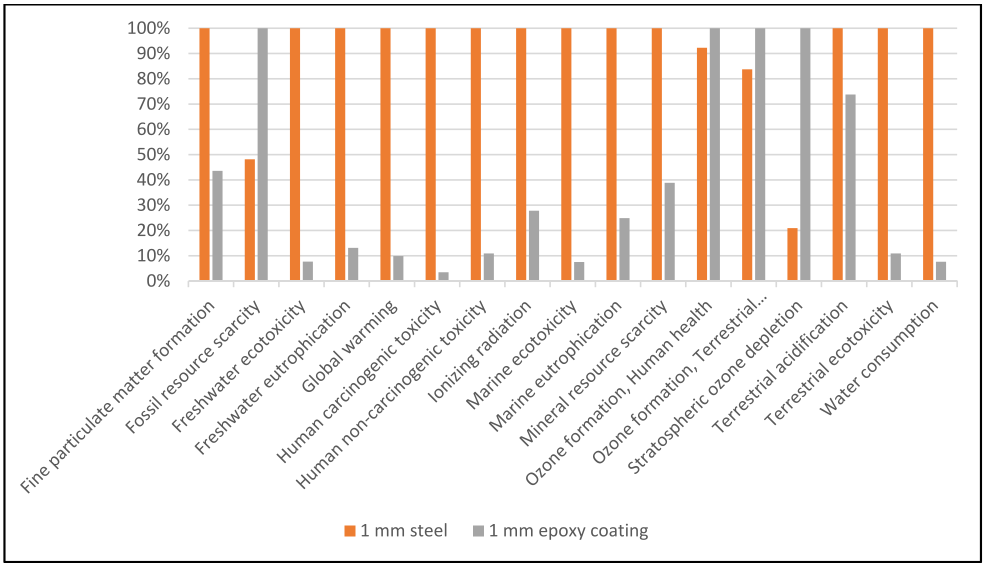

Fig. 8. Environmental impact indicator results for 1 m^2 steel in 1 mm thickness and 1 m^2 of epoxy coating in 1 mm thickness. For each indicator, the maximum result is set to 100 % and the results of the other variant are displayed in relation to this result.

Data availability

The data that has been used is confidential.

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