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Research article

Life cycle assessment of electronic, electric and nonelectric detonators; a site-specific case for Czech Republic

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ABSTRACT

The widespread use of detonators across industries such as construction and mining introduces significant environmental risks throughout their life cycle, creating a need to understand and mitigate their environmental impacts. The current study addresses this issue by evaluating the environmental footprint of three commonly used types of detonators—electronic, electric, and non-electric—through a Life Cycle Assessment (LCA). The main objective is to identify which detonator type poses the greatest environmental burden and to propose actionable strategies for impact reduction. As functional unit is chosen one piece of detonator with system boundaries set to cradle to grave. Using primary data, we constructed a comprehensive Life Cycle Inventory (LCI) and performed a Life Cycle Impact Assessment (LCIA), focusing on key impact categories. Results indicate that the electronic detonator, which excels in e.g. high variability detonation timing without losing the timing precision, exhibits the highest environmental impacts, especially concerning Freshwater Ecotoxicity, Global Warming Potential and Abiotic Fossil Depletion (e.g. 1,73E-05, 1,20E-05 and 2,12E-06 (normalized and weighted), respectively, for modules A1-A3). For the detonation itself (module A5), the non-electric detonator exhibits relatively high results for Photochemical Ozone Creation Potential (7,45E-06 kg NMVOC eq.), while the electric detonator shows highest burdens for Ecotoxicity Freshwater (5,39E-03 CTUe). Based on these findings, we recommend specific measures, such as adopting materials with recycled content, lightweight materials, bio-based and -degradable materials or alternative fuels, to support more sustainable detonator production and usage.

1. Introduction

Detonators are small devices that initiate an explosion at a specified time and require a certain amount of energy for activation. They're used primarily in commercial mining, demolition and in military operations. An explosive device is a container filled with explosive material that's designed to combust and explode when ignited by a detonator [1]. Detonators utilize a small space and a high-pressure environment to create the energy needed to initiate an explosion. These devices contain a small amount of so-called primary explosive, a sensitive material used to ignite a stronger secondary explosive, which then carries the explosion from the detonator to the explosive device. The most widely used explosives utilized in detonators include lead azide as a primary explosive and trinitrotoluene, pentaerythriol tetranitrate, hexogen and octogen (TNT, PETN, RDX, and HMX, respectively) as secondary explosives. There are three main types of detonators: electronic, electric and non-electric with electronic detonators being the most recent

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iteration [2].

Electronic detonators allow the user to alter the delay between each blast. This increased operator control ensures that the user can accurately assess the impact between each detonation, limiting excess damage to the surrounding rock and excavation site [3]. Electronic detonators also offer increased timing delay accuracy down to microseconds with longer delay ranges, unlike traditional pyrotechnic detonators [4]. New types of electronic detonators cause reduced environmental impact by minimization of over-blasting and so reduce fly-rock, dust and noise. The choice of detonator depends on the surrounding environment, safety concerns and the specific application for which they're needed.

Electric detonators utilize electric wires and currents to ignite an electric match, igniting the primary explosive within the detonator [2]. The timing within non-electric and electric detonators is not always accurate because the delay element burns at an approximate rate, not an exact rate [4]. Electric detonators are not advised for use under strong electrical conditions such as during electrical storms because stray electrical currents can result in premature detonation [5]. They're primarily used in commercial mining and military operations.

The last type, non-electric detonators, do not use electric wires to detonate the primary explosion. Instead, shock tube technology, detonating cords, and safety fuse detonators are used [5]. Non-electric shock tubes are long plastic tubes coated inside with an explosive material and are resistant to premature detonation from stray electric currents and static electricity, as well as resistant to water damage [6]. Non-electric detonators are generally used in the drilling and blasting method of tunnel excavation [4].

Currently, the most used primary explosive is lead azide. Although not a powerful explosive, the ignition of lead azide provides the activation energy needed to ignite the secondary explosives [7]. Lead azide requires a very high temperature for spontaneous combustion, meaning it's stable in storage for long periods. During manufacture, lead nitrate and residual lead azide contaminate the wastewater, which requires treatment before disposal. In addition, carbon dioxide, water, and nitrates are released into the atmosphere during production, where fossil fuels are often used as the main energy source [8]. Lead harms human and animal health, and long-term exposure damages the nervous system [9]. Environmentally friendly, nitrogen based "green" primary explosives are currently in the development phase. However, their blasting power is not as strong as the current widely used primary explosives, making lead azide a more useable option [10]. One of the few environmentally friendly, comparable primary explosives to lead azide is DBX-1 (copper(I) 5-nitrotetrazolate) [11].

Often used secondary explosives found in detonators is TNT. Unless exposed to high temperatures, explosives such as TNT are stable compounds that readily bind to organic matter in the soil, thus contaminating the surrounding soil post-detonation [12]. Effluent water from TNT production is incredibly toxic to soil and groundwater, and the products of TNT degradation can result in decreased growth and germination of plants. In addition, the US Environmental Protection Agency classifies TNT as a Class C carcinogen to humans [13]. A study on salmon alevins in a pond contaminated with TNT and its by-products in Sweden resulted in increased death frequency with increased TNT concentration [14]. TNT effluent from its manufacture and TNT-contaminated soil are both causes for concern, mainly due to their ecotoxicity. Currently, the most efficient way to dispose of TNT is through incineration due to its low soil mobility. Despite this, researchers are exploring e.g. phytoremediation as a greener alternative.

PETN, a nitrate ester, is another widely used secondary explosive in detonators [15]. PETN has a low absorption rate into biotic systems, and toxicity studies have indicated that PETN does not adversely affect human and animal health [16]. Since PETN is not very water-soluble, it does not readily bind to organic material in the soil and instead travels swiftly into groundwater systems [13].

RDX, also known as royal demolition explosive or hexogen, and HMX, also known as high melting-point explosive or octogen, are cyclic nitramines and two of the most widely used modern-day explosives [17]. They are often used as secondary explosives in detonators. HMX and RDX are both very stable in storage. HMX and RDX residues are relatively stable in the environment and water-soluble, meaning that they travel easily to groundwater and surface water surrounding detonation and manufacturing sites [18]. Concerning toxicity, the US Environmental Protection Agency has designated RDX as a possible human carcinogen that targets the nervous system, making it an environmental and human health hazard [19]. The most common method of manufacturing RDX is the Bachmann process, where hexamine reacts with nitric acid, ammonium nitrate, and acetic anhydride, producing nitrogen oxides, sulphur oxides, and acid mists as by-products, which are harmful to the environment [20]. Originally appearing as a by-product of RDX manufacture via the Bachmann process, HMX is challenging to manufacture [21]. Due to a lack of studies and available information on HMX, the US Environmental Protection Agency has not determined whether HMX is a carcinogen. Environmental remediation efforts in sites contaminated by HMX are in development, but they're still proving costly, inefficient, and not eco-friendly [18].

Upon detonation, the small amount of explosive material stored inside the detonator spreads into the surrounding environment. Depending on the purpose of the explosive device, the type of secondary explosive used in the detonator will vary. As a result, residues produced from the explosion will vary depending on the explosive and the degradation process. Many of these products from degradation (e.g., dinitrotoluene sulfonates (DNTs) and amino-DNTs from the degradation of TNT) are toxic to the surrounding environment [12]. Different detonators have different deposition rates, depending on the explosive. In a study conducted with the Canadian Department of National Defense, PETN had a much lower deposition rate of 1 × 10-7 % than RDX, which had a deposition rate of 4 × 10-3 %. A lower deposition rate translates to a smaller ecological footprint, meaning PETN is preferred regarding environmental impact [19]. Compared to TNT, HMX and RDX concentrations in the soil are typically lower. RDX and HMX do not readily bind to organic matter in the soil, instead traveling into groundwater sources [17]. Compared to RDX and HMX, PETN is generally regarded as a safer explosive to use in detonators. Despite this, HMX and RDX are more powerful explosives and are favoured for larger blasts [19].

Up-to-date, limited information on life cycle assessment (LCA) studies regarding detonators is available. No LCA studies specifically performed on detonators were found, however, LCA studies performed on hazardous components, mining or quarrying techniques are available [22–24]. Focusing purely at detonators, studies about their individual components are available for public access. Galante

Table 1
Modules declared and geographical scope of the studied detonators.

	Product stage			Construction process stage		Use stage							End of life stage				Resource recovery stage
	Raw material supply	Transport	Manufacturing	Transport	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling potential
Module	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
Modules declared	x	x	x	x	x	ND	ND	ND	ND	ND	ND	ND	x	x	x	x	x
Geography	GLO	GLO	CZE	GLO	GLO	NR	NR	NR	NR	NR	NR	NR	GLO	GLO	GLO	GLO	GLO

et al. [8] executed a life cycle inventory (LCI) study on the manufacture of lead azide, but not a full LCA study. LCA research is accessible for TNT [25]and RDX [26], which briefly mentioned HMX. Although these compounds occur in detonators, they're also used as the major explosive material in most explosives, so these LCA studies cannot be limited to their use in detonators.

While small, detonators possess the ability to create a widespread environmental impact. Every stage in a detonator's life cycle is a possible point source for pollution, from production to detonation. During production, effluent wastewater is a potential source of pollution. For example, TNT effluent is highly hazardous to soil and groundwater, resulting in ecotoxicity [12]. TNT production produces a large amount of wastewater, most of which is polluted with DNTs, which are resistant to most degradation methods [27]. In a study conducted in the Dongdagou River surrounding a TNT production plant where TNT "red water" effluent had leaked into the river in the 1970s, researchers found that levels of DNTs far exceeded acceptable levels from human and environmental health, even decades after the leak [27]. After detonation, the explosives within detonators (TNT, RDX or HMX) and their decomposition products are released into the environment, resulting in extensive soil and water contamination. No information was discovered about the emission of greenhouse gases (GHGs) by explosives nor their global warming potential. If fossil fuels are used as energy in the manufacture of explosives, then their photochemical ozone creation potential and their acidification potential would depend on the fuel used.

Not only is the production of explosives of concern but so are the plastics used in detonators. The shock tubes in detonators are composed of plastic, specifically polyethylene coating. Currently, most energy used to fuel the production of plastics and explosives is derived from fossil fuels because 80 % of the energy used globally depends on fossil fuels [28]. Over time, the production of individual detonator components and detonators slowly contributes to the depletion of fossil fuel reserves. In addition to consuming fossil fuel resources, polyethylene manufacture releases GHGs, which contributes to potential photochemical ozone creation and potential acidification [29]. The exact levels of photochemical ozone creation potential and acidification potential depend on the fuel used during manufacturing. In addition, polyethylene specifically has a significant impact in terms of global warming potential in all stages of its life cycle [30]. After detonation, polyethylene and other plastics used in detonators are released into the environment, which accumulates in the form of microplastics and releases GHGs when exposed to ultraviolet radiation. Microplastics can flow into the ocean, becoming toxic to marine ecosystems. The End of Life (EoL) of the detonators can be environmentally challenging due to residual composition of the explosives, plastic parts, or metals, depending on the EoL scenario.

Due to emerging factors having environmental impact in all stages of detonators life cycle, this study aims to fill in the current gap of knowledge in the field – a LCA of the most widely used commercial detonator types worldwide. Further goals are described in the following chapter.

2. Methods

2.1. Goal and scope

The main objective of this study is to assess the impact of various detonators life cycle on the environment. By focusing on the production phases, transport, use phase and EoL management, we provide a comprehensive synopsis of the environmental footprint associated with the examined detonators. For the transparency, this study also contains an aggregated LCI of the used components.

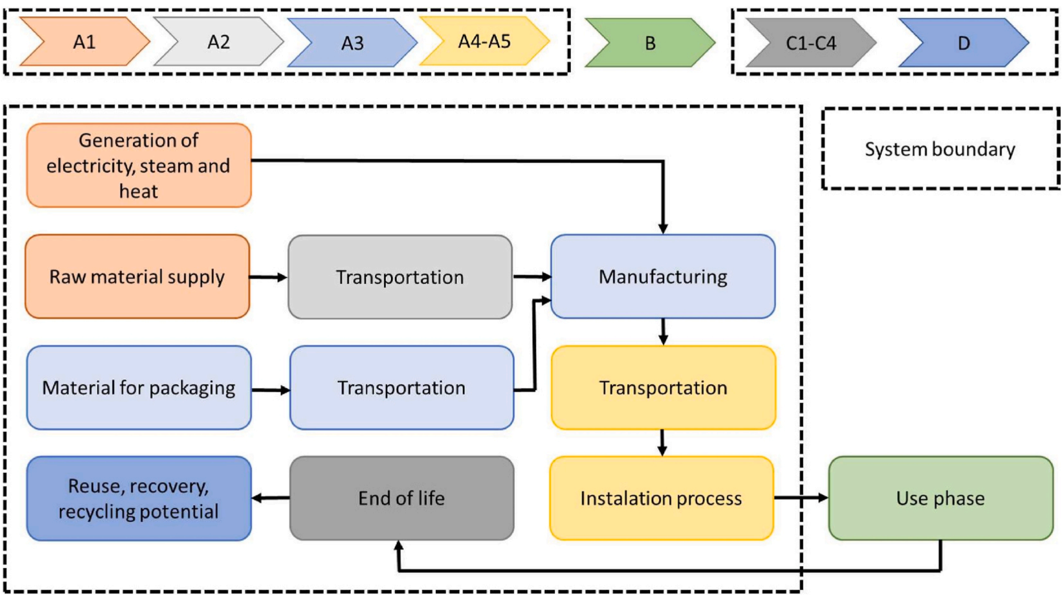

Fig. 1. Diagram of the systems' boundary of the LCA study conducted on the examined detonators.

Table 2
Content declaration of the studied detonators with accordingly highlighted common components.

ELND	Weight (kg)	ELD	Weight (kg)	NONELD	Weight (kg)
Zirconium	1,00E-05	Zirconium	1,00E-05	Th. elastomer	1,50E-06
Lead azide	8,05E-05	Iron	3,00E-05	Lead azide	6,00E-05
Others	1,40E-04	Lead azide	2,00E-04	Octogene	6,82E-05
Pentrite	8,20E-04	Hexogene	3,00E-04	Zirconium	2,58E-04
El. module	1,00E-03	Silicone	5,70E-04	Pentrite	8,00E-04
Th. elastomer	1,50E-03	Aluminium	1,42E-03	Others	2,34E-03
Silicone	1,68E-03	Others	2,27E-03	Aluminium	2,96E-03
Copper	9,89E-03	Copper	3,69E-03	Iron	7,35E-03
Iron	2,76E-02	Plastics	4,18E-03	Plastics	2,90E-02
Plastics	3,77E-02	**TOTAL**	**1,27E-02**	**TOTAL**	**4,28E-02**
TOTAL	**8,04E-02**				

*

Components same for all detonators
Components same for ELND+NONELD
Components same for ELND+ELD
Components same for ELD+NONELD

Thanks to the target on the relevant environmental categories, we are able to understand the impact of the different life cycle stages on the environment and suggest optimizations leading to decrease of the generated environmental impacts.

2.2. Methodology

The LCA method is an analytical tool that measures technological, operational, and environmental parameters of organizations or industrial enterprises involved in the production, transport, operation, or disposal of materials, equipment, fuel, or energy at any stage of a product's life cycle. It quantifies the potential environmental impacts associated with individual input and output materials and

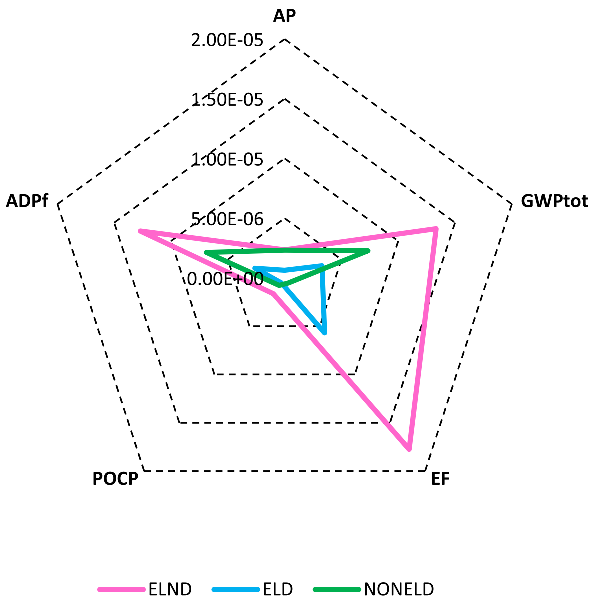

Fig. 2. Illustration of the generated burdens (normalized and weighted) by the three studied detonators for the investigated impact categories.

energies in a robust and transparent manner.

The core of the LCA method involves determining the material and energy flows into and out of the system under study, monitoring their quantity, composition, nature, and environmental significance. These flows' causes and consequences lead to changes in the environment. Data compilation starts with an inventory analysis, dividing a predefined part of the system's life cycle into unit processes and mapping the flows between them. This is followed by a life cycle impact assessment (LCIA), where specific environmental categories are chosen, obtained results are classified in the categories and, where needed, the results are also normalized and weighted. The LCIA is carried out according to EN 15804 + A2 Environmental Footprint 3.1 (EF 3.1). After LCIA follows a final interpretation.

The LCA methodology applied follows ISO 14040 and ISO 14044 standards [31,32] and meets the requirements of ISO EN 15804 + A2/AC:2021 for construction products. The LCA study utilized the software LCA for Experts by Sphera, along with internal Sphera and Ecoinvent databases. The Functional Unit (FU) for this study is one piece of detonator.

2.2.1. System boundary characterization

Basic information about specific life cycle modules is available in Table 1. This division into individual so-called modules is based on EN 15804 + A2 standard [33]. The modules represent specific life stage. Geographical scope is global (GLO) with the exception of the module A3, where geographical scope is Czech Republic (CZE) (the detonators are produced in the Czech Republic). The system boundary is cradle to grave and module D (A + C + D), specifically: production of raw materials (A1), all relevant transport down to the factory gate (A2), manufacturing (A3), transport from the plant to the site (A4), installation of the detonators (A5). The stage A5 includes also part of the life cycle in which the explosives are fulfilling their intended function (detonation). Subsequently, after the end of the detonators life, these modules are included, deconstruction (C1), transport of deconstructed materials (C2), waste processing (C3), recovery (D), and disposal (C4) of the used detonators. Most of the studied modules belong to foreground activities, which are directly related to the product system. Module D falls under the background activities. The boundaries of the study are shown in the Fig. 1.

2.3. Description of the studied detonators

This study describes LCA of three different kinds of detonators – electronic, electric and nonelectric. The electronic detonator (ELND) has important benefits such as high variability detonation timing without losing the timing precision, touchless tagging or programming by direct connection between the detonator and the equipment, superior leakage tolerance or high security level of security and safety on site. ELND is mostly used for detonations in quarries, surface or underground, metal and nonmetal mines, tunnels and construction sites. The electric detonator (ELD) offers high initiation strength, high level safety features, high level accuracy and delay intervals, great water resistance and reliability over wide temperature range. It is suitable for variety of blasting applications in the mining, quarrying and construction industries. Moreover, this detonator can be used for blasting of trenches, sewers, tunnels, shafts, drifts and raises. The nonelectric detonator (NONELD) provides high initiation strength, protected primary charge, wide range of time variability and excellent water resistance. It is used for initiation of cast boosters, high explosives or cap sensitive emulsions. The delay time variability is appropriate for tunnelling and shaft or raise mining where long delays are required between holes to allow the movement of blasted rock.

2.4. Data collection

The original data were obtained from the detonator producer and are available in the respective Environmental Product Declarations (EPDs) of the studied detonators [34–36]. The authors of this study are authors of the EPDs. The content declaration is shown in the Table 2 and the data were collected in accordance to Product Category Rules - PCR 2019:14 Version 1.3.4. Site specific data from producer are based on 1 year average for process data. Time scope less than 10-years were applied for background data (database data). Time scope less than 2-years were applied for specific data (site-specific data from producers). Each of the detonator's original composition is adapted to their specific use. For transparency, the individual items are aggregated into table shown below (e.g. metal parts, explosives, etc.).

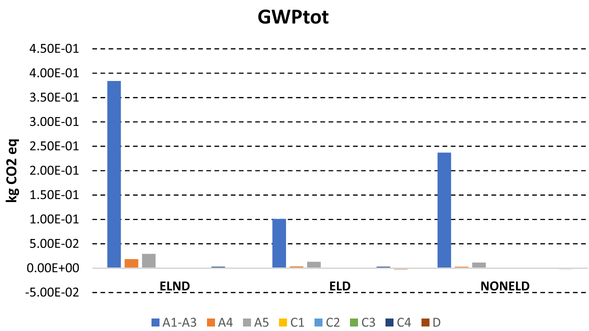

Fig. 3. Illustration of generated environmental burdens for GWPtot for all modules and studied detonators.

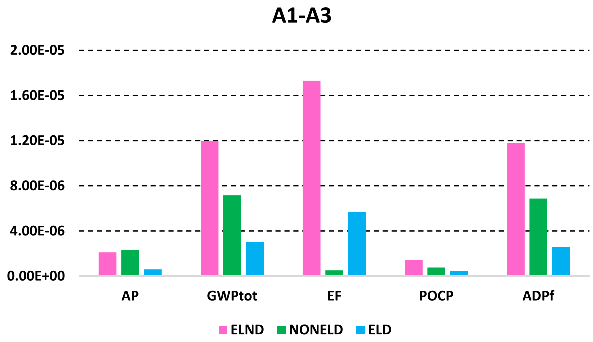

Fig. 4. Illustration of the generated environmental burdens (normalized and weighted) covering five selected impact categories for ELND, ELD and NONELD for modules A1-A3.

Table 3
Overview of results for the ELND, ELD and NONELD (normalized and weighted according to EN15804 + A2 based on EF3.1) in the studied impact categories for modules A1-A3.

Detonator	AP	GWPtot	EF	POCP	ADPf
ELND	2,12E-06	1,20E-05	1,73E-05	1,44E-06	1,18E-05
ELD	6,09E-07	3,01E-06	5,68E-06	4,63E-07	2,59E-06
NONELD	2,32E-06	7,16E-06	5,11E-07	7,66E-07	6,88E-06

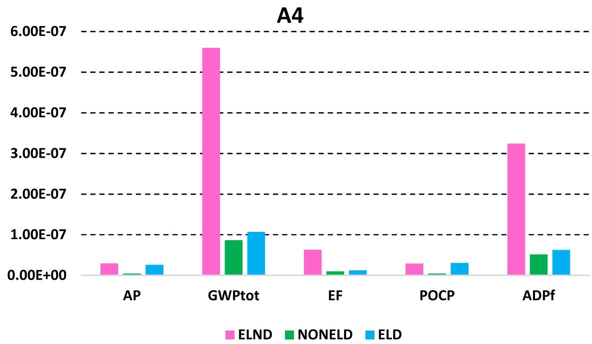

Fig. 5. Illustration of the generated environmental burdens (normalized and weighted) covering five selected impact categories for ELND, ELD and NONELD for modules A4.

The assumptions taken in consideration in this study were:

- Czech residual electricity grid mix from the Sphera database is used for the production in the production plant.
- European residual electricity grid mix from the Sphera database is used for the detonation process at the customer location.

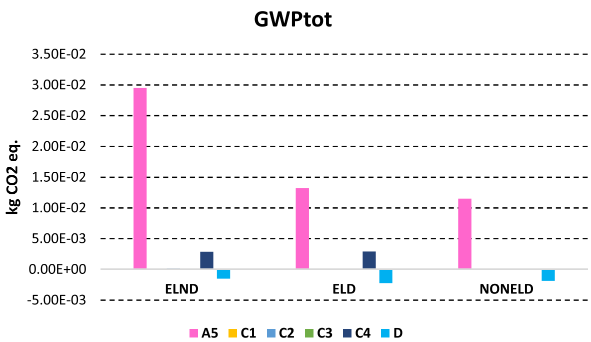

Fig. 6. Illustration of the generated environmental burdens in case of the total Global Warming Potential for ELND, ELD and NONELD.

2.5. Impact categories

On Fig. 2 are shown the categories with the highest generated environmental burdens (normalized and weighted) - Global Warming Potential (GWPtot), Abiotic Depletion Potential of fossils (ADPf), Photochemical Ozone Creation (POCP), Acidification Potential (AP) and Ecotoxicity Freshwater (EF). The focus of this study is put on these categories, as they cover majority of environmental challenges posed by detonators. The GWPtot is represented by kilograms of CO_2 equivalents or kg CO_2 eq; the ADPf is defined by MJ (the amount of energy from fossil fuels consumed/depleted during the life cycle). The POCP is expressed by kg NMVOC eq. – kilograms of non-methane volatile organic compounds, the AP is expressed by mol H+ eq. (moles of hydrogen ion equivalents) and EF by CTUe (comparative toxic units equivalents).

The GWP is investigated as emissions of CO_2, CH_4 and other GHGs are generated all over the life cycle of the detonators. Manufacturing of electronic and electric detonators involves production of materials like semiconductors, wires, and circuit boards, contributing significantly to GWP. During detonation, combustion processes release CO_2 and other greenhouse gases. The production and transportation of detonators requires resource depletion (detonators rely on fossil fuel-derived materials and energy), that is why we focused in this case on the depletion of fossil sources. The production (e.g. mining of metals) and use phase of the detonators involves emissions of volatile organic compounds (VOCs), NOx and SOx and other smog precursors, which contribute to creation of ground-level ozone [37] and environmental acidification [38] – therefore, POCP and AP are investigated. The EF is studied as during the life cycle of detonators can be released toxic substances (copper, lead), which can leak in the waters and have toxicological impact on the aquatic fauna and flora [39]. Furthermore, after detonation of the shock tube present in NONELD can be released other ecotoxic materials, having consequently negative impact on the water bodies.

3. Results & discussion

The overall normalized and weighted (EN15804 + A2 based on EF3.1) cradle to grave assessment of the three studied detonators is shown on Fig. 2.

For the discussion, we decided to split the results discussion into two parts, the first part covers modules A1-A4, the second part covers modules A5-D. The reason for this division is better results clarity (as shown in example of Fig. 3), the results for all modules and selected categories are available in Supplementary materials.

The following section discusses environmental burdens of the studied detonators for modules A1-A4.

3.1. Environmental burdens of the studied detonators, modules A1-A4

The studied environmental impacts in the result section cover GWPtot, ADPf, POCP, AP and EF. In Fig. 4 is shown comprehensive illustration of these impact categories for modules A1-A3 for the three types of studied detonators.

For enhanced readability, the results are additionally shown in Table 3.

The highest values are reached in case of ELND except of AP, NONELD displays higher values in GWPtot, POCP and ADPf than ELD and ELD shows higher impacts than NONELD in case of EF.

ELND has the most complex material composition of the studied detonators, including electronic module, which is missing in the other detonator types. Lead azide, present in highest amount in ELD, followed by ELND and lastly by NONELD, is, mostly during the manufacturing phase, causing wastewater pollution due to emissions of lead nitrate and sodium azide – chemicals which are needed for manufacture of lead azide. ELND contains highest amounts of metals, which are toxic to aquatic organisms (iron and copper) [40–42]. Especially during the phases A1 and A3 these metals leak in the environment, which probably contributes to the burden of this detonator in case of EF [43–47]. Silicone is a silica-based polymer, which can have negative effects on the environment (especially cyclic siloxanes D4 and D5 have been registered as air and water pollutants) [43]. ELND contains almost 3x higher amount of silicone, than ELD, silicone's presence in ELND probably also contributes to its impacts on EF. Aluminium, on the other hand, is not toxic to water organisms when in low concentrations ($<$1,2 mg/l) [44]. Plastic materials (namely ethylene, polyethylene, polypropylene, PVC) are in this case the most abundant part for all the three studied detonators; and, as they are mostly produced from fossil sources

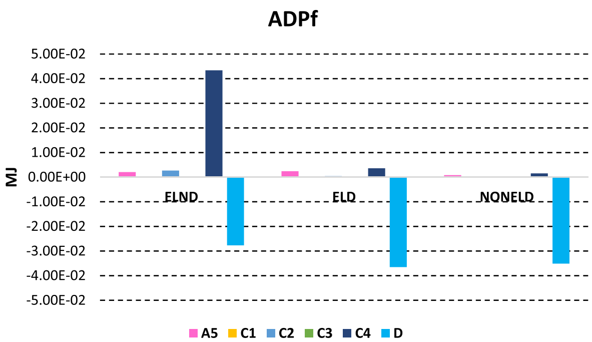

Fig. 7. Illustration of the generated environmental burdens in case of the total Abiotic Depletion Potential of fossils for ELND, ELD and NONELD.

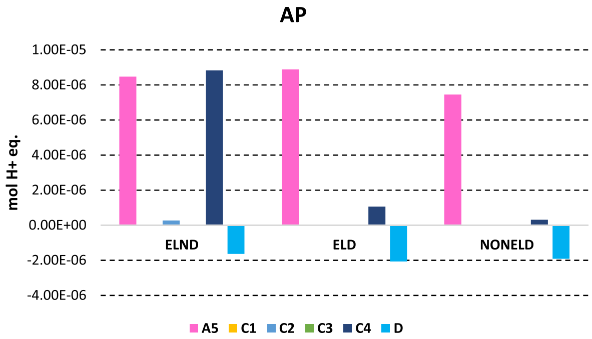

Fig. 8. Illustration of the generated environmental burdens in case of the total Acidification Potential for ELND, ELD and NONELD.

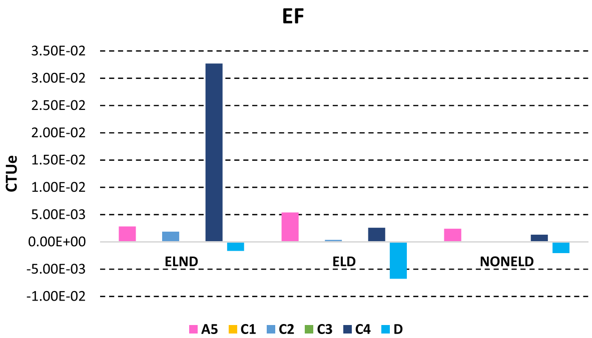

Fig. 9. Illustration of the generated environmental burdens in case of the total Ecotoxicity Freshwater for ELND, ELD and NONELD.

[45–49], they contribute significantly to ADPf as well. NONELD is heavier than ELD, containing almost 7 times higher amount of plastics. These materials contribute greatly to generated burdens in category GWPtot, as they are mostly produced from petrochemicals, which are produced from fossils fuels (i.e. crude oil and natural gas). The process of plastic production involves release of GHGs such as CO_2 or CH_4. Manufacturing of plastic resins consists from e.g. polymerization, which is a process requiring substantial amount of energy, which is often sourced from fossil fuels.

The ELND has highest weight of all the three studied detonators (it is almost twice as heavy as NONELD and six times heavier than ELD). As a FU of this study is one piece of detonator, in most of the categories the A4 module is highest for ELND (Fig. 5) – the burdens related to the transport of the detonator to the installation site are transport are directly related to its specific weight. The highest generated environmental burdens in case of ADPf are caused by the composition of fuels (in this case diesel). Generally, diesel is produced from crude oil, which is a fossil source. First, the crude oil needs to be extracted, then refined into diesel (this process is highly energetically demanding, this energy demand contributes to fossil depletion as well). The highest contribution of ELND to EF during A4 module is caused by multiple factors. During the transport, pollutants (heavy metals or polycyclic aromatic hydrocarbons) are emitted in the environment, these pollutants contribute to increase of EF [50,51]. Besides those pollutants, the vehicles can release e.g. oil and fuel, which are toxic to aquatic organisms as well. While being transported on trucks, the vehicles can release parts of tires, which break into microplastics and heavy metals. By e.g. road run-off or sewer overflow, these particles and pollutants can reach water bodies, where they further face aquatic organisms having toxic consequences on them.

3.2. Environmental burdens of the studied detonators, modules A5-D

3.2.1. Total global warming potential

In 3.2.1., for the GWPtot, the highest burdens are noticeable in case of ELND in the phase A5 (Fig. 6). Installation of this detonator is energetically demanding, and, in case of Czech Republic, the electric grid mix mostly consists from fossil fuels [52]. The ELND's high emissions of CO_2 during the installation and operation phase are caused by the need of the electric input for the detonation. In this study, the European residual grid mix was use. This grid mix consists from fossil sources of energy (61,5 %), followed by nuclear sources (30,6 %) and renewable energy sources (7,9 %) [53]. From the major contribution of fossil fuels is clear the link to high contribution of this detonator during A5 to GWPtot. Moreover, the deployment and operation of this detonator require other related activities, such as blasting or drilling [54,55] – these activities rely on fossils fuel, too.

3.2.2. Abiotic depletion potential of fossils

ELND exhibits by far the highest values in case of the module C4 in the category of ADPf – which represents the waste disposing

(Fig. 7). Plastics used in the detonators are mostly produced from non-renewable sources, which need to be first extracted, processed and refined. In case the plastics are stored at a landfill and not recycled, the demand of using virgin materials is increased and therefore the depletion of fossil sources rises. To this issue is connected energy consumption – the production of plastics requires energy, which is in the case of Czech Republic mainly consisting from fossil sources of energy. If the plastic products are stored on a landfill, the energy needed for their creation is wasted, as new plastic materials need to be produced with the new energy requirements. Next, all three detonators exhibit negative values in case of module D. The negative values represent environmental benefits associated with avoided resource extraction rather than depletion [56]. In the case of this specific category and module, this refers to generation or release of higher amount of energy, than the amount which was consumed. For this study, the assumption that paper and plastic waste is incinerated is applied, and therefore, in the module D, the benefits and loads regarding energy recovery from incineration of packaging are declared. By incineration of these two commodities is generated heat. This heat would be, under normal circumstances, produced from electricity or thermal energy consumption, however, the amount of incinerated goods contributes to spare of these energy sources, which results in environmental benefits (also known as “credits” or “negative impacts”) for this category.

3.2.3. *Photochemical ozone creation potential and acidification potential*

Contributions of the three detonators to POCP and AP are not as significant as in previous cases (Supplementary materials). In both categories are exhibited the highest impacts in case of category A5 (Fig. 8 example for AP illustration for POCP is available in Supplementary Materials). These emissions are in this case related to the detonation [57]. Among the specific procedures, the chemical processes involving release of SOx and NOx contribute greatly to AP by formation of acid rains, as well as to POCP. In case of ELND and ELD, that probably involves release of lead azide, pentrite or hexogen. Except of POCP case, NONELD shows relatively lower contributions, probably because it contains lower amounts of lead azide and octogen. In case of POCP, relatively high contributions of NONELD are probably caused by detonation of shock tube, which leads to release of hydrocarbons contributing to POCP (namely NOx and VOCs). High contributions of ELND in case of module C4 are caused by marginally higher amount of metals and plastics disposed after usage od ELND. During the disposal, especially the NOx released contribute to the POCP in this case.

3.2.4. *Ecotoxicity Freshwater*

Fig. 9 shows the results for the EF category. The highest amounts in case of module C4 for ELND are caused by the amount of plastic waste generated from the life cycle of this detonator. This plastic waste ends up at the landfill ad contributes to EF from several reasons. First, the plastic waste contains toxic chemical (stabilizers, pigments, plasticizers, organic compounds), which leach during the storage and consequent degradation of the waste in the soil and groundwater, eventually reaching freshwater sources. When these substances face aquatic fauna and flora, they get adsorbed in them and can have toxic impacts on their health, behavior or reproduction [58,59]. When in the aquatic organisms, the plastic substances get accumulated, as they are often persistent. In case the organisms containing the plastic compounds are consumed by predators, the toxic compounds enter another compartments of a food chain – a process called biomagnification [60]. During the degradation or the mechanical disintegration of the plastic compound are released microplastics in the environment. Microplastic can be than transported by leaching, but also wind into freshwater sources where they have negative impacts on aquatic environments as well [61,62]. Highest contributions of ELD to EF in module A5 can be caused by disposal of metals after the detonation.

Based on the above shown results, the ELND shows highest generated environmental impacts. To complete the discussion, it is important to mention that further material-specific impacts play an important role - production of integrated circuits and semiconductors contributes to ADPf (mining of rare metals) and EF (consequent leakage from the production) or incorporation of encapsulation materials to protect electronic components (mostly petrochemical plastics and composites, contributing to abiotic depletion). ELND are known with their provision of precise timing and programmability for blasting control. To ensure these features, more energy-intensive components are incorporated, which leads to increased environmental burdens.

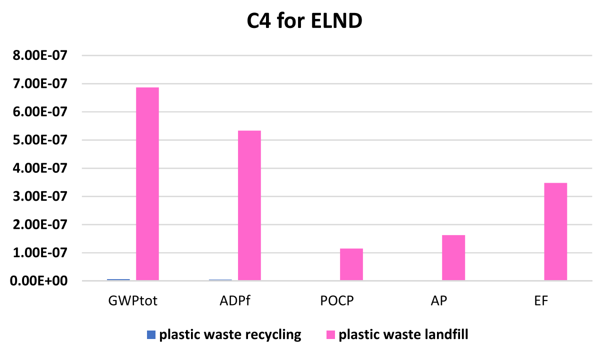

Fig. 10. Comparison of an alternative scenario (plastic waste recycling) to the current scenario (plastic waste landfilling) for ELND in module C4 (normalized and weighted).

3.3. Suggestions leading to potential decrease of the generated environmental burdens

The highest generated environmental burdens of the studied detonators are registered in the categories of ADPf, GWPTtot and EF. For the life cycle, the modules with the highest impact are the modules of category A (1–5) and module C4.

The detonators are made mostly out of plastic, followed by metals and other materials. In general, for the material supply, the emissions can be reduced by usage of metals or plastics with recycled content, less-toxic materials (e.g. lead-free materials – screen printing of non-toxic materials directly on the substrate) [63], light-weight materials [64], bio-based and -degradable plastics or optimized waste management [65]. Both of these kinds of plastics have similar properties to traditionally manufactured plastics, but are produced from renewable sources [66]. Biodegradable plastics can additionally be broken down my microbes, which can use the incoming carbon as an energy source for an additional activity, which results in lower CO_2 emissions than e.g. incineration or landfilling of conventional plastics [67]. Furthermore, use of bio-based and -degradable plastics limits the production of microplastics (depending on the type of the plastic, its breakdown, etc.), thus resulting in decreased environmental burden for EF [68].

During the transport in all of the detonators' life cycle stages is used crude oil-based diesel. In order to decrease the CO_2 emissions and the fossil depletion, the conventional diesel could be replaced by e.g. biodiesel, which is made from renewable sources (e.g. vegetable oils or fatty acid accumulating bacteria) or hydrogen [69,70].

Adoption of energies from renewable sources should be realized (electricity from photovoltaic panels, wind turbines, geothermal reservoirs) or biofuels from biomass energy, as use of energies from renewable sources (if properly planned) leads to e.g. decreased GHG emissions or decreased resource depletion.

For the category C4, in the current case the plastic waste is deposed at the landfill. In case all the generated plastic waste would be recycled, that would lead to drastic decrease of the generated environmental impact in all of the studied categories (Fig. 10). Major decrease would be observed in categories with the highest impact, the EF, ADPf and GWPtot. This result would be caused by multiple factors, e.g. reduced leachate production of lower pollution due to plastic degradation (in case of EF), lower need for virgin plastic materials or energy savings (in case of ADPf) or less greenhouse gas emissions (in case of GWPtot).

To complete the sustainable evaluation of the mentioned suggestions, further aspects such as economic feasibility or technological availability are briefly discussed. Bio-based plastics (polyhydroxyalkanoates (PHA), polyactic acid, etc.) or biofuels (bio-diesel and -ethanol or biogas) lead to lower environmental burdens (under certain conditions, e.g. lower requirements of chemical inputs), however, their costs are cca 20–30 % higher, than the prices of conventional commodities (mostly due to the raw materials' origin which require higher production costs and the lack of economies of scale) [71]. The bio-based and -degradable plastics can have different properties, such as resistance to temperature (e.g. polyactic acid has lower melting point and can degrade when exposed to elevated temperatures) and humidity. For instance, polyactic acid is more brittle compared to conventional plastics, limiting its use in high-stress environment. The technological readiness level (TRL) of bio-based and -degradable plastics is not yet competitive with conventional plastics, posing challenges for their industrialization and widespread adoption [72]. For the biofuels, their production costs can be higher than in case of conventional fuels (e.g. converting cellulosic materials into biofuels). Similarly as to bio-plastics, the technical compatibility depends on the TRL level – the current design of detonators is optimized for traditional materials, and adapting them to accommodate biofuels may necessitate extensive research and development. Furthermore, the performance of biofuels can differ in energy content combustion properties. The availability of these unconventional materials is local-dependent, Czech Republic still relies on the import of the bio-based and -degradable plastics, with the production of biofuels (especially biogas) rapidly advancing. Therefore, implementation/replacement by more sustainable components into each detonator type should be precisely evaluated by an individual fit-to-purpose analysis where the producer can compare the trade-offs of the materials with their environmental benefits.

4. Conclusions

The conclusions of the LCA study are outlined in the following points:

- The ELND has most sophisticated composition and also the highest weight of all the studied detonators.
- Generally, the ELND shows highest generated environmental burdens for EF, followed by ADPf and GWPtot.
- For modules A1-A3, ELND shows the highest generated environmental burdens, specifically in categories EF, GWPtot and ADPf (1,73E-05, 1,20E-05 and 2,12E-06, normalized and weighted).
- Specifically for module A4, the highest burdens generated are obtained for GWPtot.
- For the module A5, the NONELD exhibits relatively high results for Photochemical Ozone Creation Potential (7,45E-06 kg NMVOC eq.), while the ELD shows highest burdens for Ecotoxicity Freshwater (5,39E-03 CTUe).
- Suggestions for decrease of generated environmental burdens are given, they include e.g. use of light-weight materials, eventually biodegradable or biobased plastics or alternative fuels in transport (e.g. hydrogen).
- Alternative EoL scenario shows that plastic recycling would lead to significant decrease of the generated burdens for all categories compared to currently used landfill, that is valid especially for categories of EF, ADPf and GWPtot.
- Further aspects of implementation of more sustainable materials are given, however, the final solutions need to be determined by the detonator's producer according to its own prospective (financial, environmental, etc.).

This study provides a comprehensive analysis of all life cycle stages of the selected detonators and their associated environmental impacts. The results pinpoint the weaknesses in each stage concerning selected categories, and the subsequent discussion proposes solutions to improve the environmental profile of the detonators. For future research, we recommend deeper investigations of physical, financial and social scope of the new materials and fuels (including studies for durability, availability, performance) along with mechanical testing in field experiments or real-world conditions or adaptation of the materials into new fuels. In the future research should be included also investigations about release of microplastics from bio-based and -degradable materials (different material types, breakdown pathways, physical, chemical and biological stressors). Next, alternative detonation technologies should be investigated (with integration of catalytic convertors or chemical scavengers to mitigate harmful emissions immediately after detonation). For EoL scenarios, management of detonation residues should be further investigated. The insights gained from this research, along with future advancements, could inform policy-making and the development of industrial standards by providing robust data to guide material selection, design optimization, and sustainability benchmarks for detonator production.

CRediT authorship contribution statement

Hana Brunhoferová: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tatiana Trecáková:** Writing – original draft, Validation, Supervision, Software, Formal analysis. **Vladimír Kočí:** Writing – original draft, Supervision, Project administration, 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.

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Appendix A. Supplementary data

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