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Life Cycle Assessment of Power Utility Poles – A Review

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Abstract: *Worldwide, overhead electricity distribution is performed using poles made from various materials. The choice of the most efficient pole material is based on management strategies that integrate concerns for environmental sustainability. By quantifying environmental impacts of products, life cycle assessment (LCA) is a tool which can be very useful to decision-makers. But how, where and to which extent has it been applied to power utility poles until now, and which accomplishments and challenges can be pointed out from the findings of these LCA applications? To address these questions, a review of accessible published LCA studies of power utility poles has been carried out. By employing well established literature review methodologies, a computer search of journals, conference proceedings, and reports have been carried out and retrieved case studies have been analyzed according to the criteria derived from the four phases of LCA international standards. From a performed review process, it was realized that a total of 13 LCA case studies have been increasingly conducted during these last 26 years in only four countries around the world. The case studies included both comparative LCA of various pole materials and LCA of a single pole material. The main used utility pole materials, the main considered functional units, the main assessed impact categories, the most considered environmentally friendly pole material, and the main challenges in the field have been identified and documented. LCA constitute a useful research field when studying the sustainability of power utility poles. Although existing case studies are scarce, the review highlights several outstanding accomplishments which show what have been satisfactorily done and what needs to be done. Currently, the topic is mainly limited to USA and Swedish researchers; developing countries seem to have noting to do with and there is not yet a methodological consensus which could facilitate a deep comparison between published case studies.*

Keywords: *Environmental impacts, Life cycle assessment (LCA), Material choice, Power distribution poles, Review, Treated wood poles.*

1. Introduction

Electricity is of the highest importance for achieving all modern conveniences inherent to our modern societies. Undoubtedly Electricity has to be transported and distributed from distant power stations to consumers via relays. Electricity distribution is generally performed using underground or overhead ways. Worldwide, overhead electricity distribution is performed using utility poles. Utility poles, commonly referred to as ‘‘power poles’’, can be made alternatively of round wood, hallow wood (Veneer based composite or glulam), steel, concrete, or fiber-reinforced composite materials to name only a few [1 - 4].

Regardless of the pole material used in the electric network, it negatively affects the environment during its life cycle as it is the case for any product. These negative impacts however differ from one pole material to another. Thus, evaluating the environmental impact of product choices is increasingly important to help address sustainability issues. Moreover, considering the substitution principle which stipulates that, if possible, an environmentally harmful chemical or material shall be substituted with a less dangerous one, as documented by Hansson et al. [5], policy-makers or electric utilities faced up to the choice of the most sustainable pole material. By quantifying environmental impacts of products, life cycle assessment (LCA) is a tool which can provide a good insight to decision-makers. Heretofore, LCA have been used to understand two types of problems: (i) assessment of single type of utility pole materials to learn about their environmental performance, (ii) comparisons of alternative pole materials delivering a same service to point out the most environmentally friendly type of pole material.

The present review aims at compiling and screening papers dealing with utility poles made from varying materials in LCA perspective; in order to identify the main important parameters relevant to the topic; to point out the main accomplishments, to identify the future challenges, and to place the utility pole-related LCA studies in a historical context.

The paper begins with a brief recall of the LCA methodology followed by the description of the methodology that sustains this review. An overview of relevant information extracted from analyzed case studies according to our 3 major research questions is then provided and discussed. The paper is concluded with suggestions on potential ways to address some identified future challenges.

2. Method

This study deals with the LCA on different utility pole materials, and has been undertaken as a systematic literature review based on the guidelines both proposed by Pullin and Stewart [6], and Fantin et al. [7]. First of all, a brief conceptual basis of LCA is proposed and then, the stages of conducting a literature review according to the preceding cited authors are documented.

2.1. Conceptual basis of LCA

LCA is a methodology for evaluating the environmental impacts attributable to the products, services and processes during their life cycle from cradle to grave [8]. The idea of comprehensive environmental assessments of product was conceived in industrialized countries (England and the United States for instance) in the late 1960s and early 1970s [9, 10]. An important precursor of LCA was 'net energy analysis', a fairly hot topic during the 1970s [11]. LCA has been used in the power transmission line sector since 1992 and is an important tool for assessing the environmental impacts of utility poles [12].

Nowadays, LCA is a well-known tool for analyzing environmental impacts on a wide perspective and is also a well-integrated tool commonly used to develop products which are economical and environmentally friendly [13, 14, 15]. In fact, LCA establishes a link between the flow of materials and energy related with the life cycle of a product and the potential environmental burdens associated [16]. It identifies the points on which this product can be improved in order to reduce its overall environmental impact. It also helps to avoid problem shifting to other issues or areas when choosing a type of process or material [17].

LCA principles, requirements and guidelines are described by the ISO standards [18, 19]. With regard to these standards, LCA procedure is usually described under four distinct analytical steps: defining the goal and scope, creating the life cycle inventory (LCI), assessing the impact and finally interpreting the results. These steps are briefly described here.

Firstly, goal and scope definition consists of defining purpose, audience, methodological choice, assumptions and of drawing the studied system boundaries to ensure that no relevant part is omitted.

Secondly, the LCI consists of detailed tracking of all the flows in and out of the system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance. The quality of the LCI data and results should be sufficient to conduct the life cycle impact analysis (third phase of the LCA) in accordance with the goal and scope definition of the study [19].

Thirdly, the life cycle impact assessment (LCIA) consists of two mandatory steps: (i) selection of impact categories and classifications, and (ii) characterization. While the first step consists in selecting the impact categories which are of relevance to the study, and assigning the elementary flows from the inventory to these impact categories according to the substances'ability to contribute to different environmental problems, the second step consists in converting the emissions and resources that are assigned to each of these impact categories into indicators using impact assessment models [20]. In that way, various LCIA methodologies can be applied. They can differ in the impact categories they cover, in their selection of indicators, and in their geographical focus. The choice of the most suitable LCIA methodology is case-specific and the ILCD Handbook [20] gives support on the selection of the appropriate methodology, providing further information on the main methodologies.

Finally, the life cycle interpretation consists of evaluating LCI and LCIA results in order to identify major issues, understand the accuracy of the results, and ensure that they met the goal of the study. This is sometimes accomplished by evaluating the sensitivity of data elements, assessing the completeness and consistency of the study, and drawing conclusions and recommendations based on an understanding of how the LCA was conducted and the results were developed [21].

Regarding the previously outlined basic LCA methodology, and despite its standardized framework structure, it is flexible in supporting a wide range of goals, scopes and can fit a wide range of systems. Since LCA is data intensive, tools for conducting LCA or for supporting its different phases and applications have been devised. Most of them have been developed for particular fields of industry [22]. Various LCA databases are attached to the LCA tools and some can be used separately. There are both freely available and commercial databases. These materials data represent in general conditions in industrialized countries. Extensive data from developing and emerging countries however, is still lacking [22, 24] since LCA approach is still in its beginning there [25].

2.2. Review process

2.2.1. Research questions

A systematic literature review starts with defined research question because questions are critical to the review process in a sense that they generate the literature search terms and determine the relevant criteria. So, the research questions that guided this systematic review were:

RQ1. How much environmental study on utility poles for power transmission lines with regard to life cycle approach has been undertaken from 1990 up-to-date and who is leading them?

RQ2. How is each relevant criterion of the four steps of LCA according to ISO is considered in each study?

RQ3. What are the main accomplishments and future challenges in utility pole LCA research field?

The date of 1990 stated in RQ1 has been chosen as the starting point in accordance with the fact that it is the date where the principle of LCA as a tool for product-oriented environmental management, became widely accepted [8, 26], technical framework and consensual code of practice were published [27, 28]. To address RQ1, available published LCA of utility pole studies have been identified. To address RQ2, the intended application, the intended audience, the goal and scope, the main methodologies, and the outcomes in each case study have been extracted. With respect to RQ3 various addressed issues have been analyzed in order to distinguish what has been done from what needs to be done.

2.2.2. Search process

The focus of the research was on published environmental assessments studies on poles for power transmission lines that claimed to be life cycle based. For the literature search, the following trusted academic search engines for scientific research, were used: *Science@Direct* (http://www.sciencedirect.com), *Directory of Open Access Journals* (http://www.doaj.org/), *Current Contents* (http://www.webofknowledge.com), *Science and Technology of Advanced Materials* (http://iopscience.iop.org), *IEEE Xplore Digital Library* (ieeexplore.ieee.org/Xplore/guesthome.jsp), and *Hindawi Publishing* Corporation (www.deepdyve.com). These search engines indexe academic journals and citations from various online databases.

The search strategy used for these databases followed that devised by Dickerson et al. [29] (excepted hand searching) using the following words either single or in combination using Boolean ''or'': life cycle assessment, life cycle analysis, LCA, environmental impact, environmental profile, environment, poles, distribution poles, power poles, wood poles, steel poles, concrete poles, aluminium poles, composite poles, material choice, utility poles, poles for overhead line, impregnated poles, preservative-treated poles, alternative, poles, etc.

Secondary references were obtained via the primary paper references and via the papers where primary paper was cited. In general, citing literature was retrieved using the Google Scholar search engine (http://scholar.google.com/). Additional identification of papers was performed in addition to the above. Individual searches on key authors and institutions in the field were carried out through E-mail sent to Electric Power Research Institute (EPRI), American Wood Protection Association, American Iron and Steel Institute (AISI), American Treated Wood Council (ATWC), and via LCA discussion list, a free service offered by PRe Consultants (http://www.pre-sustainability.com). In spite of steps followed in the above search process, it is still possible that some studies have been overlooked.

This literature was obtained through an extensive literature research (from March 2015 to July 2016) and studies that were potential candidates for inclusion in our review were read more thoroughly to decide whether to include them or not.

2.2.3. Inclusion and exclusion criteria

For the purpose of this review, papers published between January 1st 1990 and July 31st 2016 were selected for inclusion. Only literature reported in English was retrieved and included in the review scope. Papers with a clear claim to be based on a life-cycle approach to estimate environmental impacts were included. Papers dealing only with life cycle cost analyses were not part of the main focus of the study. Moreover, in the context of sustainable production, some scientific studies particularly address single life stage of the poles (e.g. pole production, wood poles treatment, or pole disposal). These references with their particular foci were considered outside the scope of this review.

2.2.4. Information extraction

From each study that remained after application of the exclusion criteria, information from papers was extracted through evaluation of studies from May 1st 2016 to October 30th 2016 and were coded within the following categories: Authors, reference, countries and year, study aim, system boundaries or live cycle stages considered, functional unit, types of pole material, impact assessment methods used, impact category assessed, and data quality assessment.

3. Results and discussion

In this section, the results of the investigated studies according to the research questions stated in section 2.2.1 are presented and discussed.

3.1. Published studies on LCA of utility poles and authors (RQ1)

Following the review process, we came to a corpus of 13 case studies split in three main types: *report conference* and *Journal article*. Reports are scientific works not often peer reviewed leaded or commissioned by Government agencies, industry, and non-governmental organizations (NGO's). They are considered as an important part of the scientific literature. Conference papers refer to articles that are written with the goal of being accepted to a conference and published in collections called *Proceedings*. Journal papers refer to an article that is published in an issue of the journal. Those studies are summarized in Table 1.

Table 1: Utility pole-related LCA studies selected. Studies are alphabetically ordered.

ID	Author	Country	Year	Institution (IR / O)[a]	Paper type	Content
P1	Aquaeter[*]	USA	2013(a)	O	Report	LCA of ACZA-treated wood compared to concrete, steel and composite poles
P2	Aquaeter[*]	USA	2013 (b)	O	Report	Environmental LCA of CCA-treated wood poles compared to 3 alternatives
P3	Bolin and Smith	USA	2010	O	Report	Comparative LCA of penta-treated wood poles and composite poles
P4	Bolin and Smith	USA	2011	O	Journal article	LCA of treated wood poles compared to steel and concrete utility poles
P5	Bolin and Smith	USA	2012	O	Report	LCA procedures and findings for penta-treated utility poles
P6	Erlandsson et al.	Sweden	1992	IR	Conference	Environmental consequences of various materials in utility poles
P7	Erlandsson and Almemark	Sweden	2009	IR	Report	Background data and assumption made for an LCA on creosote poles
P8	Erlandsson	Sweden	2012	IR	Report	Comparison of environmental impacts from poles of different materials
P9	Hangyong and Hanandeh	Australia	2016	IR	Journal article	LCA of treated veneer based composite hallow utility poles
P10	Künniger and Richter	Switzerland	1995	IR	Conference	LCA of utility poles
P11	SCS Global Services[*]	USA	2013	O	Report	LCA of substitution of used wood poles by steel poles
P12	Tolle and Evers	USA	2005	O	Report	Environmental profile of utility distribution poles
P13	Wood et al.	USA	2008	O	report	Environmental impact of utility poles

[*] Author names not specified; [a] IR: Individual Researchers; O: Organizations

Two of these studies (P1 and P2) were conducted using some data compiled in three other studies (P3, P4, and P5), with the particularity that wood species and wood chemical preservative were different. Although LCA methodology is actually widely spread [30], the scarcity of published studies using LCA approach in the field of utility poles for overhead transmission lines is obvious. This scarcity can be explained by some assumptions: (i) environmental burdens of utility poles are not always addressed in consideration of all the poles life cycle stages [31 - 38]; environmental impacts are evaluated with regard to only one single phase of pole life cycle or in consideration of only one impact category [39]. (ii) In addition, it is assumed that some LCAs of utility poles are not indexed in academic search engines since they are commissioned by private organizations and results are then often confidential or not easy to retrieve. In spite of this scarcity, a look on utility pole LCA's evolution during the three decades considered in this paper reveal a slightly increasing interest for this field of study as presented in Fig. 1.

LCA studies are either conducted by independent consulting firms (organizations) or by individual researchers working in freelance or belonging to a university team of researchers. A look on geographical location of selected LCA case studies shows that inventoried studies are located in four countries: USA, Sweden, Switzerland, and Australia. No study from developing countries has been found. This can be explained by the lack of published primary data for utility pole life cycle phases, since LCA generally requires a large amount of data which results in additional cost and time. In addition, although it is commonly accepted to use literature or generic LCA data considered as secondary data that can be found in published LCAs studies or in some LCA database or Software existing primary data that must be site specific data, are either not existing or are mainly those of industries and are then often confidential. As a matter of fact, it can be quote the case of an ongoing study using LCA as a means to ensure the durability and the environmentally friendly profile of various types of water-borne treated-eucalyptus wood poles in Cameroonian context which is facing difficulties to conduct life cycle inventory stage. Data are either confidential as stated above or are not yet obtained through specific studies which must be commissioned by concerned industries or by govnmental institutions. Available primary data from developed countries can not be suitable for developing countries since geographical, social, ecological and economical realities are different. On the fringes of the preceding mentioned reasons, it can also be stated that developing countries have not yet fully integrated the concept of life cycle thinking in their environmental policies [25].

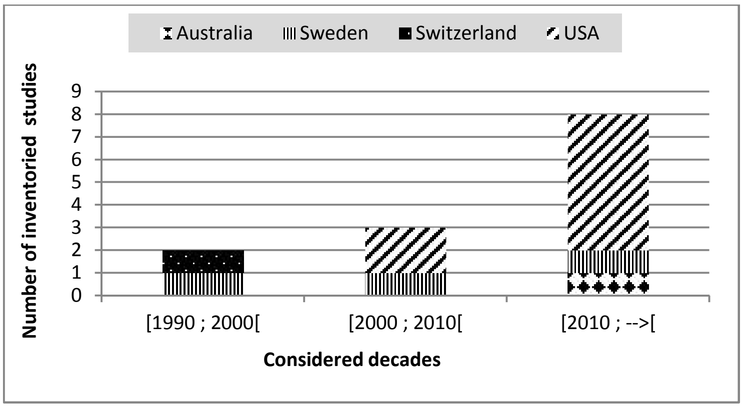

Figure: 1. Geographical distribution and variation of the number of utility poles LCA studies throughout the three considered decades.

In general, the set of reviewed studies were dominated by US researchers who have been involved in eight of the studies, in particular the Aquaeter which has been involved in 5 of the studies. Swedish researchers also contributed to three studies. Australian and Swiss researchers were respectivly authors of one study. The success of Aquaeter in applying the LCA principles in utility pole domain is supported by their strategy of constructing a frame database of primary studies related to pentachlorophenol treated wood poles and using that database in combination to other retrieved data in oder to address various specific research questions.

3.2. Relevant criteria of the four steps of LCA of utility poles (RQ2)

All the case studies were analyzed following the four steps of LCA as documented in section 2.1. For each step, a set of criteria has been selected from reviewed papers and is detailed below.

3.2.1. Step 1: Goal and scope definition

Intended application and identification of the intended audience were the main purposes of the goal, while detailed elements as description of studied poles and function, system boundary, functional unit, LCIA methodology, and types of impacts categories assessed [19] were relevant parts of the scope of the reviewed studies.

3.2.1.1. Goal

In general, the goals of all reviewed studies were clearly stated, and were mainly centred on quantifying and comparing environmental impacts associated with the utility poles made from alternative materials in a specific region. In this point of view, various comparison combinations of pole materials have been noticed. According to the statements announcing the goal of the reviewed studies, roundwood poles were the products of primary focus in all the LCA case studies and were chosen to provide a benchmark for comparison to alternative: hollow wood and non-wood products as shown in Table 2. However, one study (P9) aimed at investigating environmental burdens of only poles made of wood. These authors conducted the LCA of veneer based composite (VBC) hardwood hallow utility poles which is a pole made of an innovative material suitable for manufacturing utility pole as an alternative to replace traditional roundwood poles [4]. They investigated the environmental burdens of three disposal scenario in order to assess the appropriate end-of life treatment of their innovative product. Another study (P12) went beyond the simple comparison of environmental profile of poles and customized a life cycle screening tool used as a decision support tool for utilities companies willing to compare the life cycle environmental impact associated with different types of distribution poles. Considering screened papers, studies were mostly intended for government regulators, municipal, life cycle inventory database users, environmental advocates and utility companies (cooperative electric utilities, chemical preservative utilities) in order to provide response to new proposed legislation, to provide diagnostic tools, to improve the management of the risk associated with the usage of utility poles or chemical preservatives added to the wood to extend their lifespan, and to educate populations regarding the environmental drawbacks of various materials and chemical products in utility poles.

At present, LCA in utility poles area is mainly used by compagnies to support their environmental decision making. Some frequent applications have been noticed, namely (i) comparison of existing type of wood pole with planned alternatives, (ii) providing information and education to consumers and stakeholders, (iii) design and development of new type of hallow or composite poles.

Table 2: Selected features of reviewed utility poles LCA studies with focus on wood poles.

ID	Current pole material considered / Lifespan (years)							Length of pole (m)	Type of FU	Wood preservative		Wood specie
	W^{1}	S^{2}	C^{3}	FRC^{4}	A^{5}	G^{6}	VBC^{7}			Water-borne	Oil-borne	
P1	x/60	x/60	x/60	x/60				13.7	NA$^{\alpha}$ (Unitary)	ACZA^{a}		D. fir^{h}, Pine
P2	x/60	x/60	x/60	x/60				13.7	Unitary	CCA^{b}		Pine
P3	x/60			x/60				13.7	NA (Unitary)		PCP^{c}	R.cedar^{i}, Pine
P4	x/60	x/60	x/60					13.7	Unitary & volumebased		PCP	D. fir, R. cedar
P5	x/60	x/60	x/60					13.7	Unitary & gridbased		PCP	D. fir, Pine
P6	x/40:50	x/80	x/80		x/80			12	NA (Unitary)	CCA	Creosote	Pine
P7	x/50	x/50	x/50					9	Unitary		Creosote	Pine
P8	x/50	x/50	x/50	x/50				9	Unitary		Creosote	Pine
P9							x/25	NS†	Volumebased	ACQ^{d}		E. Cloeziana^{j}
P10	x/30*	x/60	x/60			x/30*		11	Unitary & gridbased	CCF^{e}, CCB^{f}		NS
P11	x/40	x/80						13.7	Volumebased	CCA		Pine
P12	x/[45-55]‡	x/>80‡	x/<80‡	x/[70-80]‡				12	NA (Unitary)	CCA, ACQ	PCP, CuNap^{g}	Pine, D. fir
P13	x/30	x/35	x/35	x/80^{ǂ}				13.7	NA (Unitary)	CCA		D. fir

[1] Wood (roundwood); [2] Steel; [3] Concrete; [4] Fiber-Reinforced Composite; [5] Aluminium; [6] Glulam (hallow wood); [7] Veneer Based Composite (hallow wood);
‡: Extimated lifetime slot; *: To match the 60 years' lifetime of other materials one replacment of wood pole in the grid have been considered; †: Not specified in the reviewed study;
ǂ: This FRC is a combination of high-density polyethylene (HDPE) with a small amount of recycled steel reinforcement;
α: Not available or not stated by authors but retrieved; [a] Ammoniacal Copper Zinc Arsenate; [b] Chromated Copper Arsenate; [c] Pentachlorophenol, [d] Alkaline Copper Quaternary, [e] Copper chromium fluorine, [f] Copper chromium boron, [g] Copper Naphtenate, [h] Costal Douglas fir, [i] Westren Red Cedar, [j] Eucalyptus,

3.2.1.2. Scope

- With regard to the description of studied poles and their functions, seven types of poles have been identified in reviewed paper as seen in Table 2. Wood pole (roundwood, veneer, and glulam) are, as the name suggests, made from wood. They are preserved by chemical products, and contrary to other poles materials, they are also intended for use in overhead lines for telecommunication purposes. Steel and aluminium poles have a high strength to weight ratio and do not need to be impregnated with dangerous compounds to be resistant to insect and fungi, however, they can rust. Concrete poles are made out of concrete, reinforced with steel inside which makes them even stronger. The last type of pole investigated in reviewed papers was fiber-reinforced composite poles which are made from polyester reinforced with fiberglass. The main performance requirement fulfilled by those pole materials is to be used for the construction of the distribution (medium and low voltage) overhead power lines. In consideration of the length and the lifespan, there was no standard utility pole material across studies. The alternative products have approximately the same dimensions and generally were used interchangeably with treated wood utility poles. If length was the same for all type of poles in a single study, it varied as well as pole service life across the studies as presented in Table 2.
- Regarding the system boundary, the reviewed studies featured a variety of geographical area (Table 1), and excluded the power line or telephone wire and potential different hardware or means of attachments. In addition, considered elementary or unit processes were combined into diffrent life cycle stages. Because of the variety of pole materials, life cycle stages were split across reviewed studies into two, three, four, or five stages. Some studies, namely those where the product of primary focus in the LCA was chemical-treated wood poles, split wood pole life cycle into four stages (pole production, pole treating, pole service life, and pole disposition) and other alternative materials into two stages (pole manufacture, and pole service life and disposition) (P1 - P5). Other studies considered four or five live stages regardless the pole materials assessed. In general, stage names and unit processes in stages vary according to different authors. Whatever be the number of life cycle stages considered, LCA were conducted by the authors in cradle to grave perspective, another way to express the fact that the system boundaries included all the production stages from extraction of raw materials from the earth (cradle) through to final disposition after its service life (grave); excepted (P7) who excluded the end-of-use of poles by doing a cradle-to-gate LCA. Almost all the studies included the transportation activities related to the poles' life cycle (components to pole plant, from manufacturer to utility, from utility yard to installation, removal return to yard) excepted (P8) who considered only transportation within forestry processus and did not take into account transports within other stages and between the different stages by failling to mention them; perhaps because of their low relevance to the result since they assumed that transportation is of equal importance for all studied

alternatives. The noticed hetrogeneities in system boundaries across papers might lead to different interpretation of the results.

- The choice of the functional unit (FU) was more often a unit of pole since it allowed the comparison of different pole materials on a homogeneous basis. Seven studies clearly stated the FU while the six others missed to do the same. Nevertheless, it was possible to retrieve the not explicitly stated FU since the results were given per pole excepted in (P10) where the results were also given per kilometer of 0.45kV distribution line. Clearly defined FU are presented below according to the authors' statements:

- *Functional unit: one 45-foot (13.7 m) utility pole capable of 2,400 pounds (1,087 kg) of horizontal load applied two feet from the pole's tip (P2);*
- *Life cycle inputs and outputs were quantified using functional units of 1000 cubic feet (28 cubic meters). Once compiled, the inventory data were converted to a per utility pole functional unit (P4);*
- *This report provides an LCA … based on the functional unit of each ANSI 05.1 class 4, 45-foot long pole and based on a functional unit of one mile of electric distribution line. (P5);*
- *One 9-m pole (0.4-kV transmission) with a service life of 50 years (P7);*
- *One 9 m utility pole with a lifetime of 50 years, corresponding to its service life. (P8);*
- *For this study, the functional unit is the use of a system of one million 45-foot tall, Class 2/Grade B distribution poles over a 40-year period in the South eastern US. (P11);*
- *The functional unit used in this assessment is 1-metre-length pole with 115-mm internal-diameter and 15-mm wall-thickness (P9);*

This set of explicitly stated FU extracted from the reviewed studies highlight the fact that five time out of seven, the definition of the FU is focused in the wood pole material without showing concern for others pole materials. Because of this, pole made of wood seems to be the product of prime interest in LCA of utility poles. It is also noticeable that those explicitly stated FU let to identifying three classes of FU as summarized in Table 2, namely (i) mass or volume based FU, defined by a certain mass or volume of primary raw material use in poles manufacture, e.g., 1000 cubic feet (28 cubic meters) of wood, (ii) unitary FU, defined by a unitary pole, e.g. one 9 m utility pole used in 0.4 kV distribution line with a lifetime of 50 years, and (iii) gridbased FU, defined by a certain number of poles in a delimited network region for a specific period of time, e.g., one mile of electric distribution line or one kilometer of 0.4 kV distribution line (P10) (not stated by authors but retrieved). Considering both explicitly stated and not stated FU across the reviewed studies, the distribution of these three FU types, shows that by far most LCA utility pole practitioners use a unitary functional unit. This indicates that they considere the numerical representation of the functions provided by the wood pole, which can be used to compare it with alternative material delivering the same function. In the comparative perspective, the unitary FU as stated in the above example is a relevant one since it is related to the function of the pole, and in addition, it includes not only the length of the pole but also temporal (pole lifespan) and quality constraints (pole of 2,400 pounds (1,087 kg) of horizontal load applied two feet from the pole's tip) as recommended by Cooper [40]. In this way, it is ensured that all obligatory properties as well as the duration of the pole performance are addressed in LCA.

- LCIA methodology, and types of impacts categories assessed, were also relevant parts of the scope of the reviewed studies. Related information extracted from reviewed papers are considered below in the respective sections, after the presentation of relevant elements of the second step of LCA.

3.2.2. Step 2: Life cycle inventory (LCI)

Since the purpose of developing LCI is to calculate the quantities of inputs and outputs involved in delivering a specific functional unit of the product system under study, which typically produces a list of substances with identified quantity as the outcome, it is for great importance to first collect as much data as possible in order to create a very accurate model of the system under study. For this purpose, some reviewed studies (P2, P4, P5, P7, P8, and P9) found relevant to first construct block diagram generaly called flow diagram or flowchart which shows how processes of a product system are interconnected. With this flowchart it was possible to trace all the relevant phases of all processes involved in the life cycle of utility poles. Nevertheless, although more than one pole materials were assessed in a study, some authors drew their flowchart considering only wood material (P4, P5), and literary described unit processes involved in other pole materials. However, this literary description has been the only way to describe the considered unit processes in the other studies. To overcome this unfair information treatment, (P7) took advantage of the wide range of facilities available in the LCA software they used to generate flowcharts of each pole material. To synthesize the various flowcharts one can draw, a standard example of a flowchart, describing the utility poles' system and their underlying process steps has been proposed by (P8), but his flowchart was so general that it was possible to use it for other type of products. So, considering the fact that different pole materials have different unit processes across their life cycle, it seemed difficult to draw a single flowchart that take into account more than one pole material.

LCI compilation using a process flow diagram appears in early LCA literature and has been the most common practice among LCA practitioners [41 - 43]. Moreover, it has been shown that computing LCI directly from a flowchart, as did across reviewed studies, cannot be feasible if a set of particular conditions are not met [44]. These conditions are: (i) each production process produces one material, (ii) each waste treatment process receives only one type of waste, (iii) the product system under study delivers inputs to, or receives outputs from another product system, and (iv) material or energy flows between processes do not have loop(s). Conditions from (i) to (iii) are related to the multi-functionality problem. A treatment of allocation as the solution to this multi-functionality problem across reviewed studies was not clearly specified. However only P1, P5, and P9 precised in which processes or life stage allocation has been considered (e.g. ACZA preservative active ingredient that is delivered to a treating plant as a by-product from ACZA mixing plant; discarded poles as a partly responsible of the secondary use burdens; thinned log as a by-product from the forestry industry process). Condition (iv) requires that all processes in the product system under study do not utilise their own output indirectly (i.e. in pole treatment process for example, a pole cannot also be an input of the process), this latest condition has been respected in all reviewed studies.

Collection of data on environmental inputs and outputs belonging to the pole's life cycle was generaly communicated in relation to the considered functional unit and sumarized in tables called life cycle inventory result. Three ways to report collected data have been identified across the reviewed studies : (i) data organized per unit process (P7), unit process data describe the inputs and outputs at process level, (ii) data organized per life cycle stage (P1, P6, P9), life cycle stage data describe the inputs and outputs at life stage level, and (iii) data organized regardless the unit process or the pole's life cycle stage, but considering the fact that data was inputs from technosphere, inputs from nature, or outputs to nature (P2, P3, P4, P5). Whatever has been the way of presenting data in a study, it was done the same for each type of assessed pole material. It is not worthless to mention the fact that, in the two first ways of presenting collected data in reviewed studies, data were grouped into two categories: (i) input flow, and (ii) output flow. Some authors just briefly commented on how they conducted their inventory without further information nor did they present a table sumarizing the result of LCI (P11, P12).

Concerning data collection properly speaking, the usual practice noticed in reviewed studies was to either collect data directly from the source (foreground data) or simply use the available data provided mainly in software databases or public databases (background data). Across reviewed studies, foreground data (i.e. specific to the studied poles) such as those related to forestry activities leading to wood pole prior the treatment, steel reinforcement in concrete poles, in-service pole inspections, releases of chemical preservatives to the surrounding ground from in-service poles, transport requirements for daily mobility or from one life stage to another etc. were collected either from utilities' process reportsheets or from professional judgments. Background data (i.e. not specific to the studied poles) such as those related to, water and electricity production, residual fuel oil processed, equivalence factors of chemical components, waste management, etc., where collected from LCA database programs, such as TRACI (P4), GaBi, EDIP and Ecoinvent (P7, P8), GreenDelta (P9), Ecoinvent (P12), as well as from technical books, reports, conference papers, and articles published in technical journals. In almost all the reviewed studies, in order to complete the life cycle inventories, assumptions have been used to overcome the incompleteness of LCI due to missing data.

3.2.3. Step 3: Life cycle impact assessment (LCIA)

As mentioned in section 2.1, in a LCA, all emissions and resources consumed that can be attributed to a specific product are compiled and documented in a LCI. An impact assessment is then performed on the basis of the LCI. Below, the impact categories most commonly assessed in the reviewed studies through classification, characterization and the commonly used LCIA methods and software have been indicated. How normalization and weighting, the two LCIA facultative steps are addressed, has also highlighted here.

3.2.3.1 Assessed impact categories in reviewed studies

As presented in table 3, assessed impact categories have been presented in two different groups: (i) traditional impact categories, and (ii) additional impact categories. The first group refers to impact categories usually used in most LCAs, not only those concerning utility poles, and the second group is the collection of impact categories for which operational indicators exist, but are not often included in LCA studies.

This second group has been taken into account only by P10, P11, and P12 in their study. This can be seen as the consequence of the objective of each study and also of the fact that those three authors, as well as P13, have assessed their impact categories through LCIA methods implemented by means of proprietary or personnal scripts. Two studies, namely P6 and P12, have not fully assigned the elementary flows from their LCI step to the impact categories according to the substances' ability to contribute to diffrent environmental problems, knowing that one emission can contribute to several impact categories. Consequently, retrieving characterization factors from LCA database to quantify the selected impact categories was not their concern. By acting so, they went against the mandatory LCIA's steps prescribed by ISO and known as classifiation and characterization. In addition, this bears the danger of picking single aspects of the inventory results and draw unsupported conclusions, since unconsidered subsequent LCIA phase provides additional information about how harmful emissions are to the environment and health.

Regarding the first group, the reviewed studies focused on typical LCA impact categories. In spite of the differences observed in impact categories designations across the reviewed studies, it has been possible to retrieve the number of time that a specific impact category has been considered across the studies. Moreover, as shown in table 3, the number of assessed impact categories by each reviewed study has been presented. It is noticeable that global warming potential/GWP (also designated climat change/CC, greenhouse Gas/GHG), acidification potential/AP, eutrophication potential/EP, ecotoxicity/ET, and smog potential/SP (also designated photochemical ozone formation/FOP, ozone exposure risks/OER) are the impact categories assessed by at least 75% of the authors. These five impact categories have a geographic scope varying between local and regional scale, except the global warming potential which has a global geographic scope. Since the considered studies in this paper are conducted in different geographic areas, these five impact categories can be considered as the most relevant and should at least be addressed in each utility pole LCA, expecting that these assessed impact categories are consistent with the objective of the study.

Likewise, it is noticeable that, while not an impact category, energy use/EU was also addressed by at least 75% of the authors. This energy is considered as a relative measure of the resources required for the whole life cycle stage of utility poles. It is generally well known that, products that require less input of energy consequently have less environmental impact. So, tracking energy use is a mean to allow a superficial perception on the comparison of this aspect of each pole material. As a matter of fact, energy use should be addressed when LCA results are intended to compare various pole materials.

Water use/WU (also designated Net Water Consumption/NWC) and fossil fuel/FF (also designated Fossil Depletion Potential/FDP, Energy Resouce Depletion/ERD) were also relevant impact categories addressed in reviewed studies. More than half of the authors took into consideration these two impact categories. These authors were all from USA as far as Water use is concerned; all of them were also from USA as far as fossil fuel is concerned excepted P9 who was from Australia. None of the European authors has addressed these impact categories. Since the three-fifth of the reviewed studies were conducted in USA, one can assume that impact category Water Use could be relevant for an utility pole LCA study conducted in regions with similar economic, social, and environmental caracteristics to USA. Other impacts were occasionally addressed: Solid Waste/SW, Human Toxicity Potential/HTP, and Particulate Matter Exposure/PME.

Table 3: Impact categories assessed in published utility poles LCA Studies.

ID	Impact assessment Method / software	Traditional impact categories assessed												Additional impact Categories assessed	Total
P1	TRACI / Linked Spreadsheets	GHG	FF	AP	EP	ET	SP	EU	WU						8
P2	TRACI	GHG	FF	AP	EP	ET	SP	EU	WU						8
P3	TRACI	GHG	FF	AP	EP	ET	SP	EU	WU						8
P4	TRACI	GHG	FF	AP	EP	ET	SP	EU	WU						8
P5	TRACI / Linked Spreadsheets	GHG	FF	AP	EP	ET	SP	EU	WU						8
P6		(	Ap	DG		DW		EU						)*	-
P7	EDIP, CML 2002 / Gabi	CC		AP	EP	ET	POF			HTP					6
P8	USES LCA 1.0	CC		AP	EP	ET	POF	EU		HTP					7
P9	ReCiPe Mp (H) / Green Delta	GWP	FDP	AP	EP	ET									5
P10	Heijungs et al. model	GWP		AP	EP	ET	POF	EU		HTP	SW			CAV, CWV	10
P11		CC	ERD	AP			OER		WU		UHW	ARD	PME	OTL, TBD, KSHD	11
P12	LCPROFILE^{SM}	GWP		AP		AT	SP	EU	NWC	Ca	HMQ			EHA, 7 other**	16
P13	Carnegie Mellon LCA Model	(GHG		Toxic release				EU					)*		-
Total		12	7	11	9	10	10	10	7	4	3	1	1		

GHG: *Greenhouse Gas*; FF: *Fossil Fuels*; AP: *Acidification Potential*; EP: *Eutrophication Potential*; ET: *Ecotoxicity*; SP: *Smog potential*; EU: *Energy Use*; WU: *Water Use*; Ap: *Air pollution*; DG: *Discharge to the ground*; DW: *Discharge to the water*; CC: *Climate Change*; POF: *Photochemical Ozone Formation*; HTP: *Human Toxicity Potential*; GWP: *Global Warming Potential*; FDP: *Fossil Depletion Potential*; SW: *Solid Waste*; CAV: *Critical Air Volume*; CWV: *Critical Water Volume*; ERD: *Energy Resouce Depletion (Oil)*; ARD: *Abiotic Resouce Depletion (Metal and Mineral)*; OER: *Ozone Exposure Risks*; UHW: *Untreated Hazardous Waste*; PME: *Particulate matter Exposure*; OTL: *Ocean Thermal Loading (Due to GHG emission)*; TBD: *Terrestrial Biome Disturbance (due to land use ecological impact)*; KSHD: *Key Species Habitat Disturbance (due to land use ecological impact)*; NWC: *Net Water Consumption*; HMQ: *Hazardous Material Quantity*; Ca: *Carcinogenicity*; EHA: *Ecological Habitat Alteration*; AT: *Aquatic Toxicity*

*: The outcome from the inventory step (LCI-profile step) tabulated in to emissions to air, water, and ground have not been evaluated in the life cycle impact assessment step, i.e. for example the emissions contribution to climate change, acidification, eutrophication etc.

**: The seven other additional impact categories are: Inhalation toxicity, Longevity or durability, Material persistence, Recyclability potential, Recycle content, Resource renewability/sustainability, and Toxic material mobility (upon landfilling or incineration).

Talking about the impact assessment methods and software used, first of all, it is of great importance to note that, till date, most methods and software are developed to reflect the conditions in the USA, the Northern and middle Europe. Those used across the reviewed studies were consistent with this state of the fact. As presented in table 3, assessed impact categories were conducted in most reviewed studies according to the chosen LCIA methods applied by means of dedicated LCA software (TRACI, GaBi, and Green Delta). There were also possible to implement LCIA methods in a self-made spreadsheet or even by means of private scripts (LCPROFILE^{SM} and Carnegie Mellon LCA Model).

Unless P6 and P11, all the authors clearly mention the LCIA methtods they used. P6 is usually seen as the first study of utility poles in a LCA point of view. At the time P6 was published (year 1992), LCIA methods was not yet well established; in fact, workshops on the overall technical framework, impact analysis, and data quality were held to allow consensus building on methodology and acceptable professional practice. Moreover, interest in moving beyond the LCI to analyzing the impacts of environmental resource requirements and emissions was a preoccupation of a broad base of consultants and research institutes in North America and Europe with the Society of Environmental Toxicology and Chemistry (SETAC) as a focal point for technical developments in the life-cycle assessment arena [42].

In studies where they were precise, the most commonly used LCIA methods were TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), EDIP (Environmental Design of Industrial Products), CML (Center of Environmental Science of Leiden University), and ReCiPe Midpoint H. With the exception of TRACI, all the other cited three LCIA methods were developed in Europe, and, most of the time, these underlying LCIA methods and other methods used in reviewed papers were not documented in those papers. Authors usually assumed that the intended audiences were quite familiar with LCA principles and methods.

As concerns the LCIA results, the magnitude of all the above underlined impact categories were expressed in different units and therefore can not be directly comparable in a single study (e.g. GWP, AP, EP, EU are respectively expressed in kg CO_2 eq, kg SO_2 eq, kg NO_3 eq, MJ), only when results were normalized. Likewise, the comparison was not easy to conduct across the reviewed studies because of the diversity of the case studies (in terms of number of compared pole materials assessed, life cycle stage considered) and the variety of functional units used in the reviewed papers. So, it has been not straightforward to provide a summary of LCIA results in a format allowing comparison between case studies.

3.2.3.2 Normalization and weighting

Normalization and weighting are usually used to simplify the interpretation of the results. As normalization and weighting contain additional subjective sub-steps, they are regarded as optional steps in ISO [19]. In section 3.3.1.1 we saw that each impact category has its own unit, and thus the results cannot be compared; so, normalization not only shows to what extent an impact category indicator result has a relatively high or a relatively low value compared to a reference, but also, it solves the incompatibility of units.

Normalization is carried out by means of dividing magnitude of impact categories by a selected reference value known as normalization factor. A classic method that consists in normalizing against the alternative that has greatest environmental impact in each separate category has been use by some reviewed studies. In fact, in (P1 - P5), normalization has been assessed to allow relative comparison of indicators between pole materials. So, impact indicator values were normalized to the product (ACZA, CCA, penta-treated pole, concrete pole, steel pole or fibre reinforced composite pole) having the highest cradle-to-grave value. The product with the highest value at final disposition receives a value of one, and the other products then are fractions of one. This common way of conducting normalization seems very practical and devoid of subjectivity, and should be a good method to assess normalization in LCAs intended to compare alternative products. But, this classic method has the disadvantage that there is no relative importance between the environmental impact categories obtained. In general, to overcome this disadvantage, one can normalize with regard to what the natural environment can tolerate annually. This second way of conducting normalization is briefly described in P7 and P8 which also assesse normalization in their respective studies. This second way is fully described in the method developed by the IVL [45, 46] and has greater environmental relevance since the LCIA leads to results where the relative importance between the different environmental impact categories is illustrated. So, the normalization method used in P7 and P8 is based on what the natural environment can tolerate. This acceptable annual environment load is divided by the number of individuals in the analyzed system (i.e. geographically). In this way, an annual quota can be obtained which corresponds to the maximum emissions that one person may give rise to, assuming that everyone is allowed the same emission quota. This per capita emission is called a person equivalent (Pe). These authors found that this type of normalization gives a numerical value which is easy to communicate and intuitively easy to understand the meaning of.

Only those seven cited authors have assessed normalization in their study, the other limited their LCIA to the two above cited mandatory steps. The reason for this limited use of normalization can be linked either to frequent criticisms of this approach, in particular regards to the referent regional or global systems used for scaling which are often poorly estimated leading to uncertainty [47]; or to the lack of emission data and/or characterisation factors leading to bias [48].

With regard to the weighting step, it is by definition not based on natural science and is very subjective. As a matter of fact, it consists in deciding, on the base of subjective value choices, the relative importance of already characterized and normalized impact categories (occasionally with regards to an aggregated single score). In (P12), although, the authors did not follow the LCIA steps that must be assessed before the weighting step, they directly presented the impact category scores of each pole material in the form of weighted total scores. These weighted total scores were calculated by multiplying each individual impact category score by the weighting factor (they previously defined) and then summing all weighted criteria scores for a given distribution pole. As the authors precised, the limitation in the use of the weighted, total scores is that, they can be subjective, because they represent the preferences of the expert team conducting LCA who may not offer a valid statistical sample of the population. Also, weighted scores can only be calculated if all of the impact criteria raw scores are known. In contrast, there are also advantages to using the weighted, total scores. Weighting the scores permits them to be summed for easier comparison of the overall environmental acceptability of different pole types, particularly when different criteria do not always favor a single pole type. Evaluating weighted total scores based on more than one perspective insures acceptance by a broader range of stakeholders. On the fringes of above cited authors, and, among of the other reviewed studies, none of the papers go through this weighting step. Knowing that almost all the reviewed studies were intended to environmental communication, the reason of the nonexistence of this step can be explained by the fact that, when the results are intended to compare competing products and they are to be presented to the public, weighting is not allowed according to the ISO series [49].

3.2.4. Step 4: Interpretation

According to the ISO [19], the final stage of LCA, interpretation, consists of extracting conclusions based on the inventory analysis and impact assessment, in such a way that results of the LCA can be presented and used for decision-making. This assessment may at least include the identification of the significant issues based on the results of the LCA phases, an evaluation that considers sensitivity and uncertainty analysis.

3.2.4.1. Identification of the significant issues

Identification of the significant issues across reviewed studies led to highlight a total of ten studies that provided ways to rank the different pole materials according their environmentally friendly qualities with regards to their overall contribution to environmental impact. Moreover, considering the noticed heterogeneity in the choice of functional unit, system boundaries, impact assessment methods, impact categories assessed as well as in the display of results, it has not been possible to sum up these contribution analyses in one consistent way. Instead, and for illustration purpose, this study presents at the same time in table 4, the ranking of the environmentally friendly pole materials where the attributed numbers represent the preference order (1 is more desirable than 2), and the pole material having the lowest or the highest impact indicator score with regards to the most assessed impact categories in LCA of power utility poles.

It is noticeable that four types of pole materials (wood, steel, concrete, and fiber-reincorced composite) are the most used in power transmission lines, and among them, wood is the most environmentally friendly alternative; six impact categories have been seen as the most assessed in LCA dedicated to utility poles for overhead electric lines. Regarding the concluding step in the life cycle of a utility pole across the reviewed studies, the final disposition of poles, namely wood poles, has been identified as a recurrent issue since there were a great variety of chemical preservatives used to protect wood poles against biological decay. Different scenarios to manage the end-of-use of treated wood poles have been implemented knowing that used poles can be landfill as waste, incinerated as fuel to produce process heat, or recycled as fence posts or landscaping. The chosen options were consistent with the type of preservative, the legislation of related country, and the fact that whatever be the option, the release of the chemical preservatives into the environment is a large big concern. In (P4), where preservative was pentachlorophenol, an oil borne product, 47 percent of out-of-service wooden utility poles were recycled for other treated wood use, 21 percent were recycled for energy recovery, and 32 percent were disposed in landfills. The proportion of used utility poles to each post-use fate was set up according to the current industry practice in USA. In the same way, (P12) analysed pole disposition through incineration and landfilling as well as P10 who analysed the scenario where 90 percent of out-of-service wood poles were combusted in incinerator with efficient exhaut filtering while the remaining 10 percent were left to decomposition. Although once in the landfill the chemicals in the preservatives leach into the ground water, landfill was the only option in (P1, P11, and P13) while (P9) analyzed successively all the three end of use management. On the contrary P8 considered landfill as a much worse alternative for dealing with used treated pole given that there is bound energy in the pole which is lost when sent to landfill. This can seem inconsistent in relation to other studies if the nature of the chemical preservative is not taken into consideration.

Table 4: Ranking of environmentally friendly pole materials

ID	Environmentally friendly pole						Pole material having the lowest|highest impact indicator score					
	W^1	S^2	C^3	FRC^4	A^5	G^6	GHG	AP	EP	ET	SP	EU
P1	1	2	4	3			W|C	W|C	W|C	W|C	W|C	W|C
P2	1	2	4	3			W|C	W|C	W|C	W|C	W|C	W|C
P3	1			2			W|FRC	W|FRC	W|FRC	W|FRC	FRC|W	W|FRC
P4	1	2	3				W|C	W|C	W|C	W|C	S|W	W|C
P5	1	2	3				W|C	W|C	W|C	W|C	S|W	W|C
P6	No available data to estimate						W$_{CCA}$|A	*n.a.*	*n.a.*	*n.a.*	*n.a.*	W$_{CCA}$|A
P7	2*	3	1				W|S	W=C|S	W|S	C|S	C|S	*n.a*
P8	1	3	2	2			W|S	W|S	W|S	C|S	C|S	W|S
P9		†										
P10	1	4	2			3	W$_{CCB}$|S	W$_{CCB}$|S	W$_{CCB}$|S	C|W$_{CCB}$	C|S	W$_{CCB}$|S
P11		‡					S|W	W|S	*n.a*	*n.a*	W|S	*n.a*
P12	1	1	2	2**			W$_{ACQ}$|S	W$_{CCA}$|W$_{ACQ}$	*n.a*	C|W$_{CCA}$	W$_{ACQ}$|W$_{PCP}$	W$_{CCB}$|FRC
P13	1	3	2				W|S	*n.a.*	*n.a.*	*n.a.*	*n.a.*	W|S

[1]Wood; [2]Steel; [3]Concrete; [4]Fiber-Reinforced Composite; 5Aluminium; [6]Glulam (hallow wood);

*: The authors asserted that an overall assessment will favour the creosote treated wood poles as the ecologically most sustainable alternative since their proposed results probably underestimate the impacts of steel poles and concrete poles on ecotoxicity and human toxicity;

†: Ranking and impact category score not applicable since only one type of pole material has been addressed;

‡: LCA have been conducted in pole material substitution point of view (no possible ranking)

n.a.: not assessed;

**: The study has been conducted according two perspectives: the electric utility perspective and the national policy perspective. The ranking of environmental friendly pole material proposed in the table is that of the national policy perspective; the ranking is different with regard to the electric utility perspective: S (1), C (1), FRC (1), W (2).

3.2.4.2. Sensitivity and uncertainty analyses

Sensitivity analysis consists in the evaluation of the effects of changes in data and methodological choices over LCIA results, while uncertainty analysis is the procedure to determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the LCIA [19]. Sensitivity and uncertainty analyses should be performed in order to better reflect the accuracy of LCI and LCA studies.

Except (P6, P7, P12, and P13), all the references have assessed uncertainty analysis. In (P1, P2, P3, P4, P5, and P9), a gravity analysis, which is a statistical procedure that identifies those data having the greatest contribution to the indicator result, has been first of all conducted in order to identify items that must be investigated with increased priority. These cited authors and the others, identified several sources of uncertainty which can be categorized in two groups according to the classification proposed by Huijbregts [50]: (i) parameter uncertainty and (ii) uncertainty due to choices. Considering the first group, inaccurate emission measurement (e.g. chemical preservative released during pole treatment, storage, service life, and at disposition, GHGs releasing during the decay of wood in landfills, etc.), data collected from different sources in literature and assumptions made on input data (e.g.data related to transportation required during pole life cycle) was the main sources of this category of uncertainty. The second group of uncertainty was mainly related to the choice of the functional unit, especially the considerated pole lifespan. The uncertainty due to inaccurate emission measurement is large because of variations in production facility containment structure integrity, production facility housekeeping practices, regional location of the treating facility and service location, and disposition.

In almost all the papers dealing with uncertainy, parameter uncertainty and uncertainty due to choices were simply mentioned without been conducted or without explanations on how they must be addressed. However, authors completed a sensitivity analysis to determine the magnitude resulting from assumptions and uncertainties identified in the LCI and the impact on LCA results. Sensitivity analysis has been carried out based on various criteria, including modifying allowable emissions, simulating different volumes of key substances, and varying several operational factors. Among the key parameters adjusted to perform the sensitivity analyses, there were chemical preservative retentions, pole service life, post-use fate of treated wood poles, recycling rates of steel, disposition situation of concrete, electricity production model, etc. In almost all the concerned references, the sensitivity analysis was conducted in form of scenario evaluation. This was done by comparing one adjusted key parameter with basis scenario values and by showing the increase or decrease of each impact category. For instance, in (P9), it has been shown that changing the transportation distance from 50 to 150 km increases total global warming potential by 9%, acidification impact by 16% and fossil depletion by 6%. Likewise, (P4) shown that, when steel poles are assessed with a service life of 99 years, decreases in all impact indicators are observed. Across reviewed studies, sensitivity results were communicated in very diverse manners, ranging from a simple statement to several paragraphs of discussion showing how impact indicators evaluated in baseline scenario vary according the modifications made on imput data.

3.3. Main accomplishments and future challenges in utility pole LCA research field (RQ3)

LCA of power utility poles is a topic that progressively raises increasing interest in the scientific literature as presented in fig.1. Several outstanding accomplishments and contributions have been provided and can be considered as the basis for the LCAs in the power transmission utility poles sector, but a lot more work is certainly required and several challenges should still be faced to contribute to the ongoing discussion on sensitive issues of LCA in general.

3.3.1. Main accomplishments

To date, in power utility pole-related studies, LCA has been used to analyse pole life cycle stages, to identify high-impact activities, to compare pole materials, and to a lesser degree, to guide improvement trajectories. The studies in this review have been screened for patterns and singularities in an attempt to characterize the state-of-the-art of LCA applied to power utility pole. A number of accomplishments have been highlighted and can be split in two categories: (i) achieved accomplishments (that can be considered as completed satisfactorily) and (ii) unfinished accomplishments (that can be considered as not finally treated). This second category of accomplishment is documented below in section 3.3.2 as future challenges.

By considering the first category, one can first of all point out that there is an obvious scarcity of published studies using LCA approach in the field of utility poles for overhead transmission lines. In addition, while all the retrieved and considered LCA studies describe in various environmental considerations for power utility poles in Europe, Australia, and USA, there are no comparable studies in the literature from developing countries especially.

The achieved accomplishments can be listed as follows:

- In the field of addressing utility poles in a LCA point of view, (P6) is usually seen as the first authors who conducted a study.
- There is a noticeable evolution in the number of LCA studies related to utility poles in consideration of each decade of the passed 26 years considered in this paper.
- Poles made of roundwood, glulam (hallowwood), veneer, steel, concrete, fiber-reinforced composite, and aluminium, are the main pole materials assessed in the reviewed studies, and are compared in LCA perspective to enable robust decision making of pole material selection. However, pole made of wood seems to be the product of prime interest in LCA of utility poles.
- Disregarding the variation in the denomination of the impact categories, two groups of impact categories have been identified: traditional impact categories and additional impact categories. Among the first group, the most assessed impact categories were GHG, AP, EP, ET, SP, EU. These relevant environmental impacts, except the EU which is not really an impact category, are output related impact categories i.e. they contribute to the environmental pollution while EU which is generally linked to fossil fuel can be ranged in input related impact categories i.e. it contributes to the resources depletion. Moreover, these impacts are of a local scope (e.g., ecotoxicity impacts due to the site's residual contamination), of a regional scope (e.g., acidification associated with NO_X emissions from burning treated wood) or global (e.g., climate change due to greenhouse gas emissions). In short, LCA allows for consideration of activities at each pole life cycle and addresses environmental impacts that can occur at a local, regional, and global level.
- Those above cited relevant impact categories can be seen as potential candidates for standardization in utility pole LCA studies. However, it must be clear in mind that a particular environmental mechanism can have very important impacts in one region, but not in another. So, due to the unavoidable contextualization in the LCIA phase which consists in recognizing which environmental mechanisms are relevant in a local context, the decision to address one of those local standardized impact categories must be consistent with local environmental sensibilities.
- Although wood poles seem to be more environmentally friendly with regard to the most assessed impact categorie, a general figure depicting in an absolute way the most friendly pole material can not be drawn.
- Knowing that almost all the reviewed studies have been conducted in comparative perspective, one can think that it seems irrelevant to conduct a LCA of a single pole material. Not that it is any of the case; the study of P9 set a good exemple of the LCA of a single pole material. The importance is to have a relevant objectif and to be consistent with across the study.

  On the fringes of these achieved accomplishments, other accomplishments have been considered; but the differences observed across the reviewed studies lead to consider them among the future challenges of power utility poles LCA studies.

3.3.2. Future challenges

As regards the power utility pole-specific methodological concerns, to date there is no agreement concerning methodological choices for carrying out and presenting LCAs in this field of study. Although some efforts (considered here as unfinished accomplishments) have been made to streamline the utility pole LCA methodology, there remain some unsolved issues as listed below.

- Different flow diagrams or flowcharts which show how processes of utility pole life stages are interconnected have been proposed to trace all the relevant phases of all processes involved in the life cycle of utility poles. Given that more than one pole materials were assessed in a study, and that different pole materials have different unit processes across their life cycle, it has seemed difficult to draw a single flowchart which takes into consideration all the assessed pole materials.
- Impact categories have been assessed through various LCIA methods and different software varying from the most sophisticated (TRACI, GaBi, etc.) to the simplest one (self-made linked spreadsheet). An attempt to implement a software (LCPROFILE^{SM}) dedicated only to utility pole have been set up in a specific context to compare the environmental profiles of various pole materials and to select the best one. This software has been developed to reflect the conditions in the USA and could not be appropriate in other contexts if supplement work is not undertaken to improve its consistency and spread its usefulness. Be that as it may, since utility poles are embedded in a specific environment, are subject to a specific climate, interact with a specific technosphere, and can face local environmental issues (in addition to global environmental issues), one can first modeling different software that reflect different environmental realities and then produce an universal one on the basis of a consensual work.
- Contradictions seem to appear in the results when confronting both studies conducted in USA and in Europe especially in consideration of some relevant impact categories and two types of pole materials (concrete and steel). Regarding those considerated impact categories, while in USA concrete has the highest impact indicator score, in Europe it is steel (see Table 4). Knowing that LCA methodology is normalized, utility poles LCA practitioners should try a bit harder to minimize such disparities.
- Regarding the life cycle stages, the final disposition of poles, especially of wood poles, has been identified as a significant issue since there were not only a great variety of chemical preservatives used to protect wood poles against biological decay, but also a great variation in the legislation of concerned countries. Different scenarios to manage the end-of-use of treated wood poles have been implemented knowing that used poles can be landfill as waste, incinerated as fuel to produce process heat, or recycled as fence posts or landscaping. Moreover it has been seen that whatever be the chosen options which were consistent with the type of preservative and the legislation of related country, the release of the chemical preservatives remaining in the discarded wood poles into the environment is a large big concern that must be addressed deeply and specially in waste management scenarios.
- Inaccurate emission measurement, data collected from different sources in literature, assumptions made on input data, and subjectivity in choice of the functional unit have been identified as the main sources of uncertainty. Those uncertainties have been pointed out and categorized as parameter uncertainty and uncertainty due to choices. If uncertainty due to choises have been made operational in some reviewed studies with the help of expert judgement, peer review, or scenario analysis, which shown the effect on LCA outcomes of several combinations of choices; none of the study has addressed parameter uncertainty in a way to make it operational in utility pole LCA outcomes according to the standard procedures (probabilistic simulation, correlation, regression analysis etc.) as proposed by Heijungs and Huijbregts [51]. Knowing that addressing uncertainty is among the greatest of the grand challenges, not only for utility poles LCA, but for other LCA, this issue should be considered with interest in future utility pole-related LCA studies or in a possible proposed methodology.

4. Conclusions

This paper presents an overview on LCA of utility poles for overhead power transmission lines found in scientific literature. Although it shows that existing case study literature is scarce, selected studies are considered not to be exhaustive since some LCAs of utility poles is made for the specific use of decision-makers and could not be indexed in academic search engines screened in this paper. All LCA case studies have been done in developed countries; namely in Europe, USA, and Australia. No comparable studies in the literature from developing countries have been found. The results in this study suggest that the current output of utility poles LCA studies is mainly supported by US and Swedish researchers. Specifically, the *Aquaeter* and the *IVL Swedish Environmental Research Institute Ltd* respectively represented by Bolin et al. and by Erlandsson et al., are currently the leading organizations in terms of undertaking LCA of utility poles. Some key parameters (functional unit, pole life cycle stages, pole lifetimes, chemical preservatives for wood pole, assumptions made, and standard database and software used) vary a lot across studies, it results in a lack of methodological consensus which do not allow to provide a proper LCIA results comparison among reviewed papers.

Nevertheless, it has been shown that among the environmental impact categories considered in utility pole for overhead transmission lines, GHG, AP, EP, ET, SP, and EU are the most addressed in the reviewed studies. Since this set of six impact categories are widely applied, across reviewed studies, it seems a good candidate for standardization. Moreover, it has been shown that although poles made of wood seem to be more environmentally friendly than those made from other materials with regard to the most assessed impact categories, none of the pole materials has advantages for all environmental effets. Consequently, a general figure depicting in an absolute way the most friendly pole material cannot be drawn. Several outstanding accomplishments split in this study as achieved accomplishments and unfinished accomplishments have been identified and treated as what have been satisfactorily done and what needs to be done.

This review, which can be considered as the first in the utility pole-related LCA studies, suffers from a number of limitations. In particular, due to the noticeable distance in the results of reviewed studies and their restricted number, we have limited ourselves to the first three steps of the method for improving reliability and relevance of LCA reviews proposed by Fantin et al. [7]. We plan to repeat this study at the end of 2019, not only to track the real progress of LCA of utility poles in the whole three considered decades, but also to extend this study by undertaking the two missing steps of Fantin et al. proposal (LCA review of tap and bottled water), hoping that some other utility pole-related LCA studies will be undertaken by that time. In addition, since LCA case studies have been done only in developed countries, sustainability indicators in pole production, use and end-of-use need to be developed for developing countries and used, in order to target environmental and energy considerations worldwide. We are currently thinking about a methodology to perform this last aspect.

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