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Authors:	Dario Trabucco, Tenured Researcher in Building Technology, IUAV University of Venice Antony Wood, Executive Director, Council on Tall Buildings and Urban Habitat Olivier Vassart, Head of Structural Long Projects, ArcelorMittal Nicoleta Popa, Senior Research Engineer, ArcelorMittal
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A Whole LCA of the Sustainable Aspects of Structural Systems in Tall Buildings

Dario Trabucco[1,2,†], Antony Wood[2], Olivier Vassart[3], and Nicoletta Popa[3]

[1]*IUAV University of Venice, Venice, Italy*
[2]*Council on Tall Buildings and Urban Habitat, Chicago, USA*
[3]*ArcelorMittal, Luxembourg*

Abstract

This paper summarizes the results of a two-year-long research project conducted by the CTBUH on the life cycle assessment (LCA) of tall building structural systems. The research project was made possible thanks to a $300,000 contribution from ArcelorMittal and the support of some of the most important structural engineering firms and players in the tall building industry. The research analyzed all life phases of a tall building's structural system: the extraction and production of its materials, transportation to the site, construction operations, final demolition of the building, and the end-of-life of the materials. The impact of the building structure during the operational phase (i.e., impact on daily energy consumption, maintenance, and suitability to changes) was also investigated, but no significant impacts were identified during this phase.

Keywords: Embodied energy, Life cycle analysis, Structural engineering, Sustainability

1. Introduction

1.1. Goal definition of this study

The *intended application* of this study is to inform the community of professionals and researchers specializing in tall buildings on the environmental performance of the most common structural systems by providing the most accurate, up-to-date analysis on two key impact categories: Global Warming Potential (GWP) and Embodied Energy (EE). The *limitations of this study* are represented by the fact that only two impact categories (GWP and EE) are considered here, while other impact categories may lead to different results. Similarly, the obtained results are influenced by the quality of the information used, both in terms of environmental data (i.e., the "quality" and representativeness of the environmental data contained in the international databases used in the study) and data completeness (for example, environmental data on the end-of life of tall buildings simply doesn't exist, and had to be collected specifically for this research). The studied scenarios are representative of the most common structural systems for buildings of this height.

The main *reason to conduct this study* is that there is a lack of reliable and comprehensive information on the relevance of the construction phase for the environmental sustainability of tall buildings, and a *comparison on* the relative importance of selecting various structural materials and structural systems for a tall building is needed. The intended *audience* of this *public* study is the community of tall building experts involved in the ownership, development, design, planning, construction, operation, maintenance, and research of tall buildings. The study was *commissioned and sponsored* by ArcelorMittal, the world's largest steel producer.

1.2. Scope definition of this study

The scope of this study is to inform the *comparative assertions* on the environmental sustainability of the above-grade structural systems for tall buildings, quantifying the environmental impact of relative sectors in the building industry. The data used is *consistent* with the structural material quantities necessary to erect the above-grade structure of a tall office building, with a given shape that is subject to code-compliant wind and seismic forces. The referenced structure is hypothetically located in downtown Chicago, United States.

The *functional unit* for this study is represented by the whole structure of the building, corresponding to 246 and 490 meters in height (60- and 120-story equivalent scenarios). The "per net square meter" or "per floor" results are not considered in this study as the precise take-up of the floor area caused by the different structural systems can hardly be determined here. The study omits the occupancy phase of the building, and it is thus not applicable to a specific duration of use, as research evidence showed that the impact of the structural components during a building's use phase was not measurable, and the environmental performance of the building is predominantly controlled by

†Corresponding author: Dario Trabucco
Tel: +39-41-257-1276
E-mail: dtrabucco@ctbuh.org

other aspects of the design (function, curtain wall performance, MEP systems, etc).

Two different *impact categories* are considered for this study: Climate Change and Resource Depletion, with GWP and EE as their selected *indicators*.

The *system boundaries* of the study are extended to the whole life of the building structure, from the production and transportation of materials to the building site, through the construction and use phase (subsequently excluded from the results), the demolition of the building, and the recycling potentialities of the various components (presented as additional information since it is beyond the system boundaries set by European Norm 15978 "Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method") (European Norm, 15978:2011).

2. Life Cycle Inventory Analysis

2.1. Quantities of materials

The *analyzed system* is represented by the functional unit (i.e., the entire building structure) delivered by the construction company to the other contractors that will transform the structural skeleton for future use (interior fit-out, cladding, installation of MEP, etc.).

Inputs to the analyzed system were *modeled by attributing* the material quantities to the supply-chain of the construction company, represented by the material suppliers and the transport companies that deliver the materials to the site. With the use phase being excluded for the above mentioned reasons, the functional unit is then transferred in the end-of-life scenario to a demolition company, whose "inputs" (energy) and "outputs" (emissions and debris) are quantified.

2.2. Production of materials

All the above mentioned quantities were calculated thanks to the support of several industry leaders who voluntarily contributed to the research by modeling specific structural scenarios. Inputs to the construction process, represented by the quantities of materials needed to construct the functional unit of this study, were calculated by some of the world's leading engineering firms on the basis of a design brief prepared by the CTBUH.

Eight different configurations for the vertical structure were identified for the 60-story tower, and eight for the 120-story variation (See Fig. 1). A total of 16 scenarios were thus identified, with each scenario submitted to two design firms, so as to obtain 32 "bills of materials" that represent the basis of information for the subsequent pha-

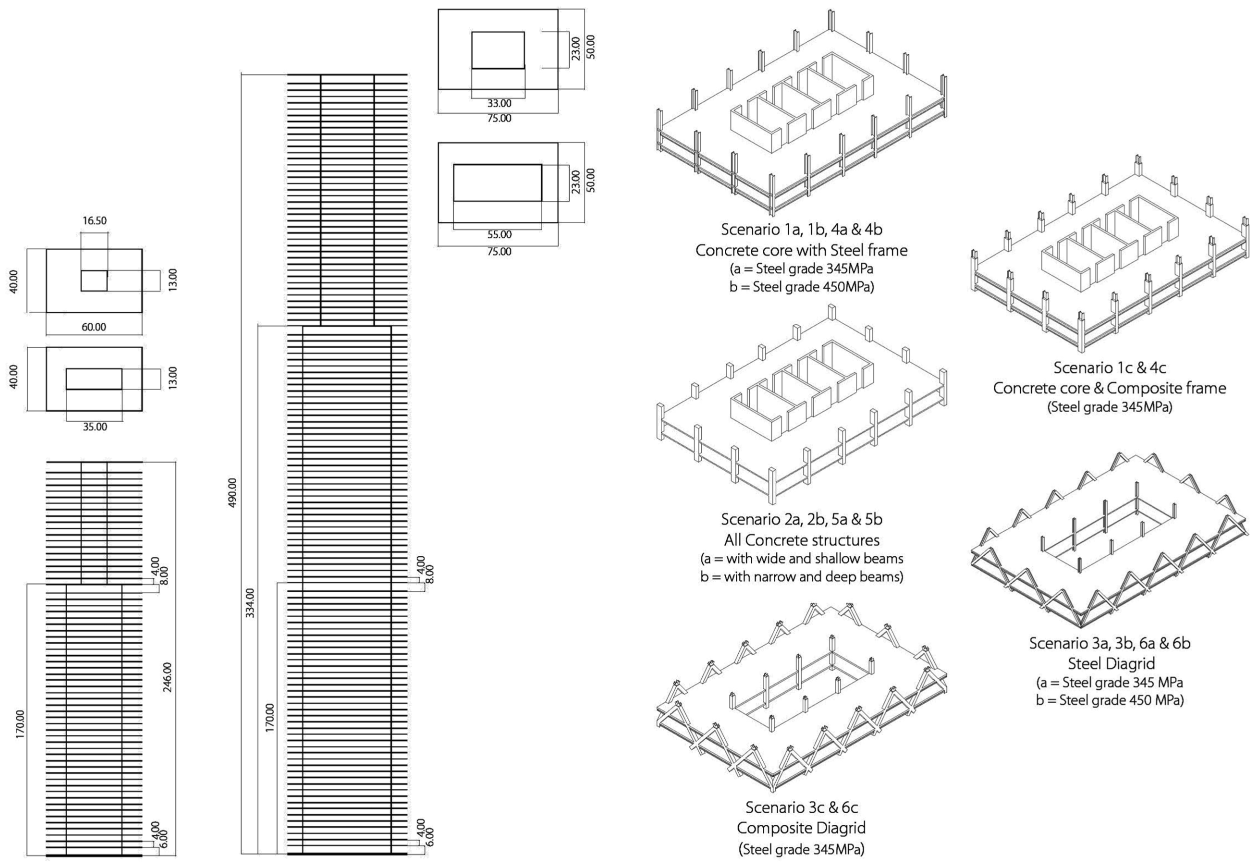

Figure 1. Description of the 16 scenarios considered by the research. Source: CTBUH.

ses of this research. The resulting quantities were integrated with data on the horizontal structural elements (i.e., floor beams, floor slabs, etc.) obtained from a comparison with buildings of the same size, function, and scale to those considered for the research.

This phase regards the A1-A3 steps as described by the European Norm (EN) 15978.

The results of this section, directly derived from participating engineering firms, are presented in the table below (Table 1).

2.3. Construction process and transportation phase

The transportation phase was modeled on the basis of the real material transportation distances for the construction of a tall office building completed in 2009 in Downtown Chicago, for which the engineering firm responsible for the comparative real building was able to provide a comprehensive set of information.

Data for the on-site operations was calculated by contacting the suppliers of the largest machines operating on the building site during the erection of the structures (cranes and concrete pumps) to receive information on their energy

Table 1. Inventory of Materials. Source: CTBUH

Short description	Scenario Number	10ksi Concrete [t]	9ksi Concrete [t]	8ksi Concrete [t]	6ksi Concrete [t]	4-5ksi Concrete [t]	Steel Rebar [t]	WWF [t]	Steel Studs [t]	Metal Decking [t]	Steel Beams [t]	Steel Columns [t]	Steel Trusses [t]	Fireproofing Spray [t]
Normal Steel + concrete core	1a	11,944	-	12,857	6,077	28,424	1,388	260	25	1,212	4,011	1,971	186	1,651
Normal Steel + concrete core	1a	-	-	7,608	12,036	28,424	957	260	25	1,212	3,949	1,614	333	1,651
High Strenght + concrete core	1b	11,944	-	12,857	6,077	28,424	1,388	260	25	1,212	4,011	1,840	186	1,651
High Strenght + concrete core	1b	-	-	7,608	12,036	28,424	957	260	25	1,212	3,949	1,307	333	1,651
Concrete core and composite frame	1c	13,032	-	13,844	8,218	28,424	1,554	260	25	1,212	4,011	786	186	1,600
Concrete core and composite frame	1c	-	-	8,758	13,761	28,424	1,122	260	25	1,212	3,949	667	333	1,600
All concrete wide and shallow beams	2a	24,150	-	13,340	6,900	80,803	3,332	260	-	-	-	-	-	-
All concrete wide and shallow beams	2a	5,962	-	31,464	8,280	80,803	7,481	260	-	-	-	-	-	-
All concrete narrow and deep beams	2b	24,150	-	13,340	6,900	58,939	3,281	260	-	-	-	-	-	-
All concrete narrow and deep beams	2b	33,782	-	6,955	5,631	58,939	6,309	260	-	-	-	-	-	-
All steel diagrid normal steel	3a	-	-	-	-	28,424	548	260	25	1,212	4,862	5,850	1,800	1,742
All steel diagrid normal steel	3a	-	-	-	-	28,424	548	260	25	1,212	4,156	2,050	4,970	1,742
All steel diagrid HS steel	3b	-	-	-	-	28,424	548	260	25	1,212	4,756	4,250	1,700	1,742
All steel diagrid HS steel	3b	-	-	-	-	28,424	548	260	25	1,212	4,051	1,640	4,900	1,742
Composite diagrid	3c	-	-	-	13,617	28,424	778	260	25	1,212	4,848	3,050	1,900	1,600
Composite diagrid	3c	6,049	-	5,221	3,243	28,424	1,188	260	25	1,212	4,236	610	1,490	1,600
Normal Steel + concrete core	4a	76,864	-	23,242	64,209	83,543	7,424	764	75	3,563	11,861	25,923	2,641	4,844

Table 1. Inventory of Materials. Source: CTBUH (Continued)

Short description	Scenario Number	10ksi Concrete [t]	9ksi Concrete [t]	8ksi Concrete [t]	6ksi Concrete [t]	4-5ksi Concrete [t]	Steel Rebar [t]	WWF [t]	Steel Studs [t]	Metal Decking [t]	Steel Beams [t]	Steel Columns [t]	Steel Trusses [t]	Fireproofing Spray [t]
Normal Steel + concrete core	4a	144,744	-	29,938	-	83,543	10,683	764	75	3,563	11,608	19,369	5,125	4,844
High Strenght + concrete core	4b	76,864	-	23,242	64,209	83,543	7,424	764	75	3,563	11,861	25,923	2,641	4,844
High Strenght + concrete core	4b	144,744	-	29,938	-	83,543	10,683	764	75	3,563	11,608	16,420	5,125	4,844
Concrete core and composite frame	4c	85,130	-	32,563	81,793	83,543	8,028	764	75	3,563	11,861	5,526	2,641	4,702
Concrete core and composite frame	4c	179,399	-	38,511	-	83,543	10,560	764	75	3,563	11,608	3,538	4,990	4,702
All concrete wide and shallow beams	5a	104,871	-	65,368	40,242	237,496	17,064	764	-	-	-	-	-	-
All concrete wide and shallow beams	5a	139,518	-	82,184	49,981	237,496	20,399	764	-	-	-	-	-	-
All concrete narrow and deep beams	5b	104,871	-	65,368	40,242	173,232	16,915	764	-	-	-	-	-	-
All concrete narrow and deep beams	5b	139,518	-	82,184	49,981	173,232	21,330	764	-	-	-	-	-	-
All steel diagrid normal steel	6a	-	-	-	-	83,543	1,611	764	75	3,563	18,062	14,850	54,900	5,284
All steel diagrid normal steel	6a	116,667	71,029	41,765	-	83,543	9,991	764	75	3,563	11,147	784	29,719	5,166
All steel diagrid HS steel	6b	-	-	-	-	83,543	1,611	764	75	3,563	18,062	11,700	54,900	5,284
All steel diagrid HS steel	6b	116,667	71,029	41,765	-	83,543	9,991	764	75	3,563	11,147	784	29,719	5,166
Composite diagrid	6c	56,925	-	31,050	37,261	83,543	7,911	764	75	3,563	18,062	-	8,550	4,702
Composite diagrid	6c	55,306	24,724	17,281	32,799	83,543	5,620	764	75	3,563	10,952	648	21,138	4,702

consumption. This phase regards the A4-A5 steps as described by EN15978.

2.4. End of life

The end-of-life quantities were obtained by consulting with three large demolition contractors operating at the international scale. Only the 60-story scenario was used in this circumstance as the demolition of such a building would still significantly exceed any previously demolished tall building. The same documentation that was provided to the engineering firms for the creation of the "bills of materials" was provided to the demolition firms in order to gather information on how a demolition project on this scale would be handled, which kind of machinery would be involved, and how long the demolition job would take.

The responses of the consulted demolition contractors informed the creation of an end-of-life scenario for the various scenarios of the building structures.

The demolition materials are considered to be hauled to the closest scrapyard and concrete recycling plant to the building site.

This phase regards the C1-C4 steps as described by EN 15978.

3. Life Cycle Impact Assessment - Results

3.1. Classification and characterization

The environment effects caused by each material or ope-

Table 2. Characterization factors used for this research. Source: CTBUH

Values Per Kg	GWP (Kg CO_2 Equivalent)/kg	Embodied Energy (MJ/kg)
Concrete French Concrete (US EPDs)		
9-10ksi Concrete [Kg]-C70	0,16 (0,24)	1,23 (1,60)
8ksi Concrete [Kg]-C55	0,17 (0,20)	1,25 (1,49)
6ksi Concrete [Kg]-C40	0,15 (0,17)	1,12 (1,28)
4-5ksi Concrete [Kg] - C30/37	0,11 (0,15)	0,83 (1,22)
Structural Steel Components		
Steel Plates [Kg]	2.46	26.07
Steel Beams [Kg]	1.21	15.36
Steel Columns [Kg]	1.14	14.80
Steel Trusses [Kg]	1.14	14.80
Reinforcing steel Components		
Steel Rebar [Kg]	1.24	16.42
WWF [Kg]	1.24	16.42
Other Components		
Steel Studs [Kg]	2.16	23.71
Metal Decking [Kg]	2.56	28.22
Fireproofing Spray [Kg]	0.26	4.37
Credit for scrap	-1.51	-13.4
Energy Carriers		
Diesel [liter]	0.61	53.24
Electricity [MJ final energy]	0.19	2.97

ration accounted for in the life cycle inventory is assessed against the two selected *impact categories* (*Climate Change* and *Resource Depletion*) by monitoring their impacts on the Global Warming Potential (GWP) and Embodied Energy (EE) *indicators*.

Table 2 presents the *characterization factor* (environmental properties, in this case Kilograms of CO2 equivalent per kilogram of material, and Mega Joules per kilogram of material) for each *elementary flow* (material, operation, input, etc.) of the process, that is: it expresses how much that flow contributes to the *impact category indicator* being considered (GWP and EE). Most of these characterization factors are derived from the Ecoinvent database, while some have been calculated by CTBUH on the

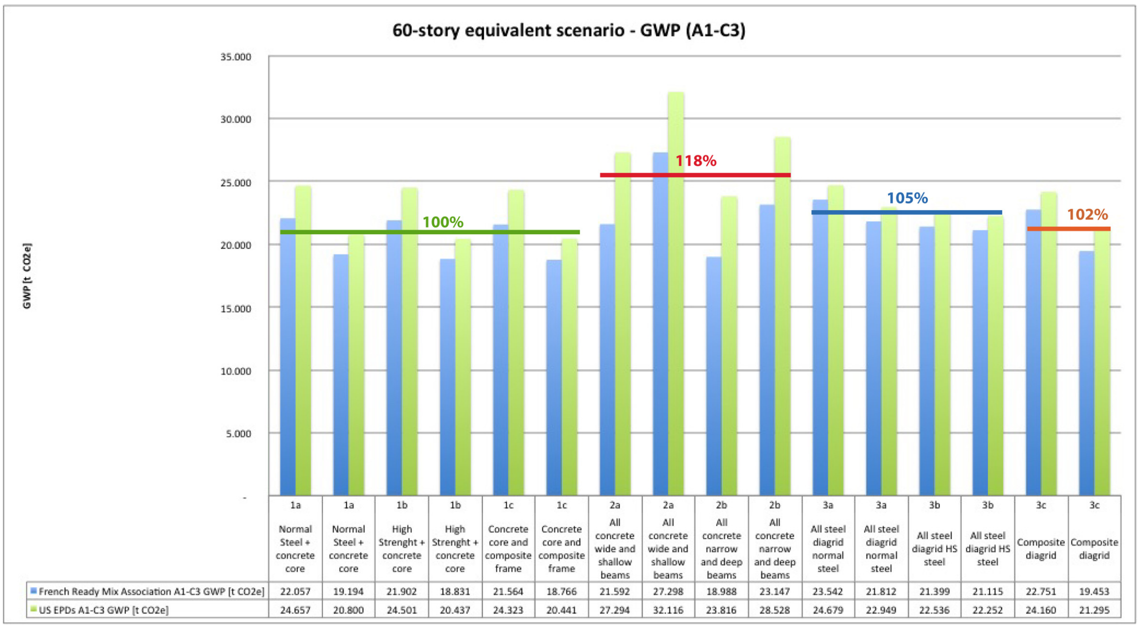

Figure 2. Graph 1: LCA results of the 60-story equivalent scenario for global warming potential. Source: CTBUH.

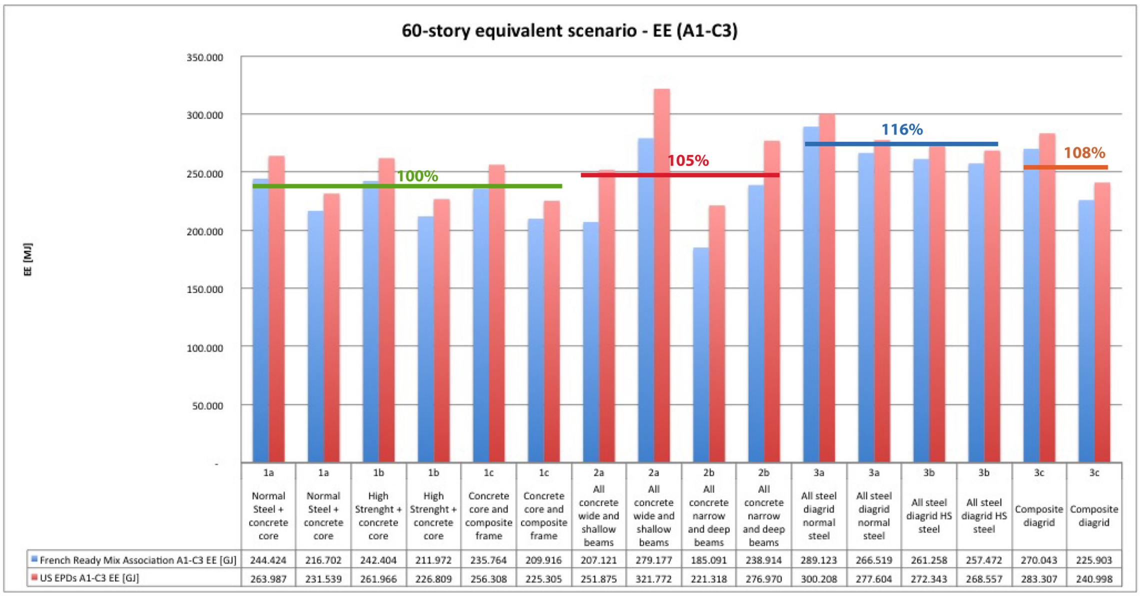

Figure 3. Graph 2: LCA results of the 60-story equivalent scenario for embodied energy. Source: CTBUH.

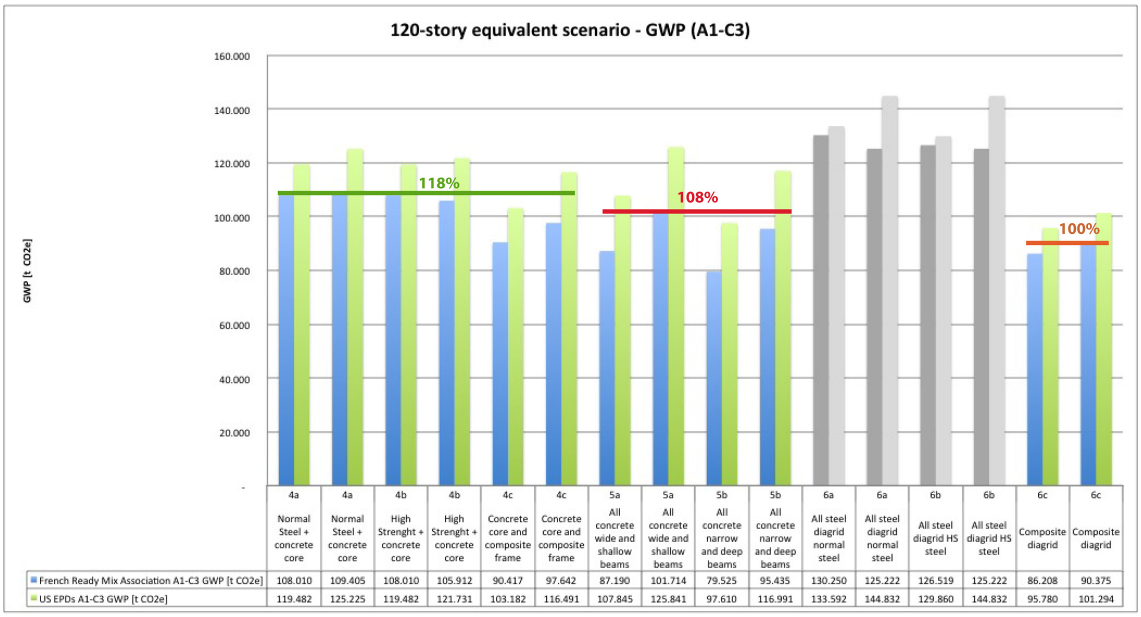

Figure 4. Graph 3: LCA results of the 120-story equivalent scenario for global warming potential. The structural solution for scenarios 6a and 6b (steel diagrid) proved to be unsuitable for a 120-meter tower. Source: CTBUH.

basis of the information provided by the firms and companies supporting the research.

3.2. Considerations on the characterization factors for concrete

Concrete is a material whose mix changes according to a broad range of variables. Compressive strength is usually the main parameter being considered, but other factors influence the final *mix design* of the product, such as the workability, the required strength gain over time, etc. Also, other external factors not dependent on design decisions can have an impact on the mix design, such as the distance from the mixing plant, the external temperature when concrete is poured, etc. For this reason, it is very difficult to identify a unique characterization factor for concrete. Consequently, the research used two different

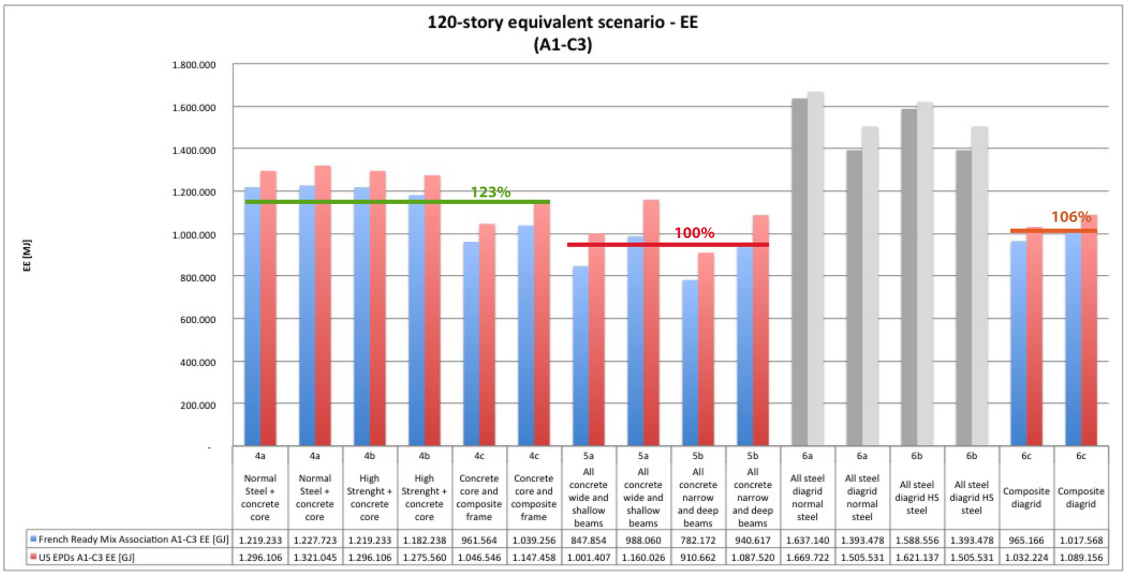

Figure 5. Graph 4: LCA results of the 120-story equivalent scenario for embodied energy. The structural solution for scenarios 6a and 6b (steel diagrid) proved to be unsuitable for a 120-meter tower. Source: CTBUH.

sets of values for each concrete grade. One is based on the data released by the Syndicat National du Beton Pret a l'Emploi, and a second set is calculated on the basis of over 1,500 EPDs (Environmental Product Declarations) issued by concrete producers in the San Francisco area. As can be seen in Table 2, where both characterization factors are presented, the specific concrete mixes, but also the contour factors (mix of energy used at the plant, chemical composition of the raw materials, modernity of the production infrastructure, etc.) can have a significant impact on the environmental performance of concrete.

3.3. Results

The key research results are summarized in Figs. 2~5, which represent the Global Warming Potential and Embodied Energy results of all 16 scenarios being considered. Each scenario has been studied by two different engineering firms, which provided an inventory of materials. The 32 resulting inventories were multiplied for the two different sets of characterization factors, so as to reflect the variable environmental impacts of concrete. Figs. 2~5 represent the entire life cycle (A1-C3) as described by EN 15978, which corresponds to the whole construction phase, from the extraction of raw materials to the installation on the building.

It should be noted that the results of the 6a and 6b scenarios, which were supposed to correspond to the "all-steel diagrid scenario", present two very different results from one engineering firm to the other. Both firms agree that the building has an unusual shape for this structural system. Consequently, one firm decided to add a concrete core to help the external diagrid withstand the horizontal forces acting on the building. The other firm over-designed the steel diagrid to maintain the "all-steel" idea, thus leading to the use of an unusual amount of structural steel.

3.4. Life cycle impact assessment - additional information beyond the system boundary

The European Norm 15978 prescribes that the system boundaries of a building LCA must be limited to the disposal of the demolition debris. However, it cannot be denied that most materials have a residual value even after the demolition of the building.

In this standard, a Module D which takes into account the Benefits and loads beyond the system boundary has been introduced.

Metals, for example, are almost entirely recycled for the production of new products that will have the same properties of the original materials (thus resulting in no downcycling). Consequently, after a building is dismantled, all of the metal parts are sorted from the demolition waste and sent to a scrapyard for recycling. A "credit" can be obtained for the steel parts forming the structure of a building. These include steel sections, rebar, steel decks, and so on. Some of the scenarios considered by this research produce such a high quantity of steel scrap that this "credit" is capable of offsetting the environmental "burden" caused by directing the remaining demolition waste (mainly concrete) to a landfill.

The high recycling potential is an intrinsic value of steel and metals in general, and this "credit" should be communicated as part of the additional information necessary to make an informed decision on the environmental properties of the various design solutions assessed by this research (ATHENA, 2002; WorldSteel Association, 2011; American Iron and Steel Institute, 2013). The impact of the Mo-

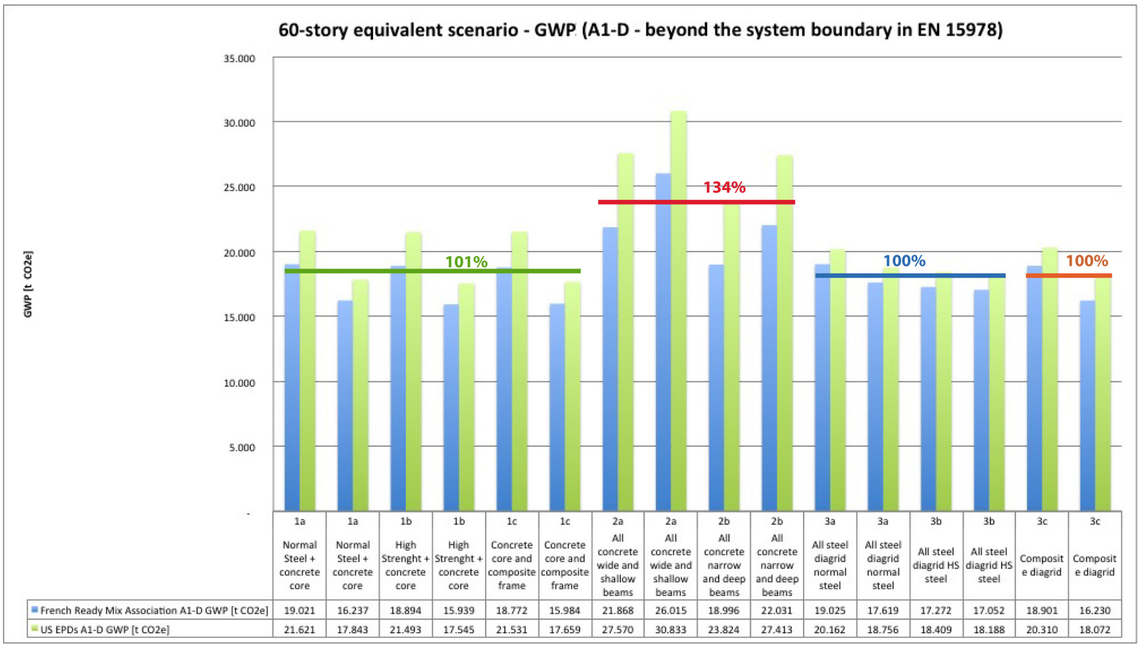

Figure 6. Graph 5: Results beyond the system boundaries as allowed by EN 15978. Source: CTBUH.

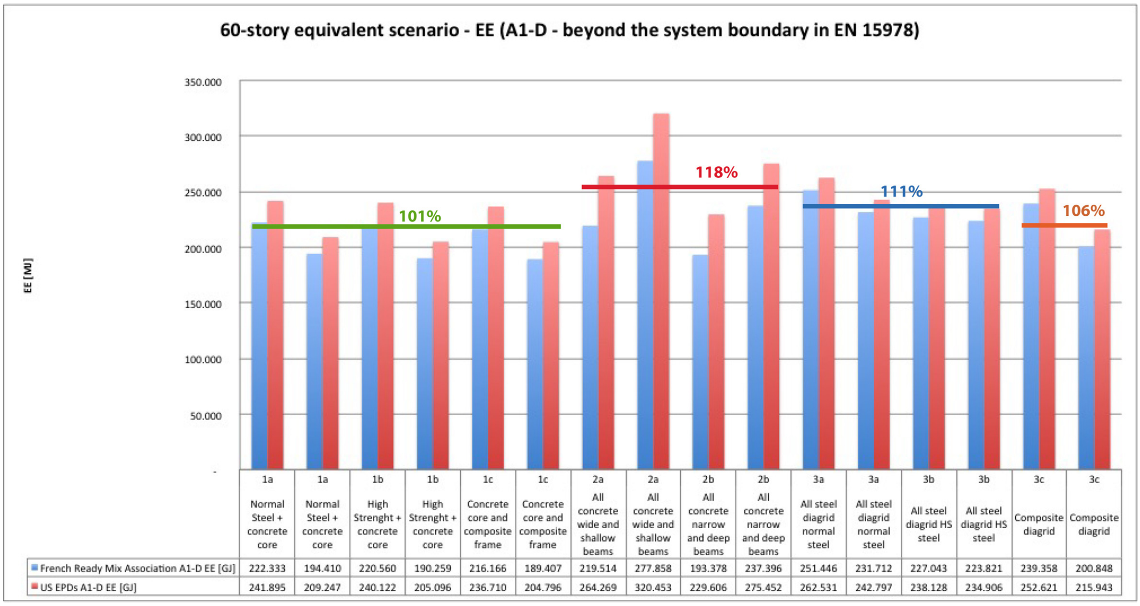

Figure 7. Graph 6: Results beyond the system boundaries as allowed by EN 15978. Source: CTBUH.

dule D is evident when the credit for scrap is included as in Figs. 6~9.

4. Conclusions

4.1. General conclusions

1 - After completing this 24-month-long research exercise, the researchers agree that lifecycle assessment as a discipline is still very sensitive, where small decisions can have a significant impact on the final results. Consequently, the research results are applicable only to the specific case studies considered here, with the system boundaries and all the other conditions and limitations that are valid for this research, and they cannot be used to give conclusive results on the sustainability of different structural systems or structural materials in general.

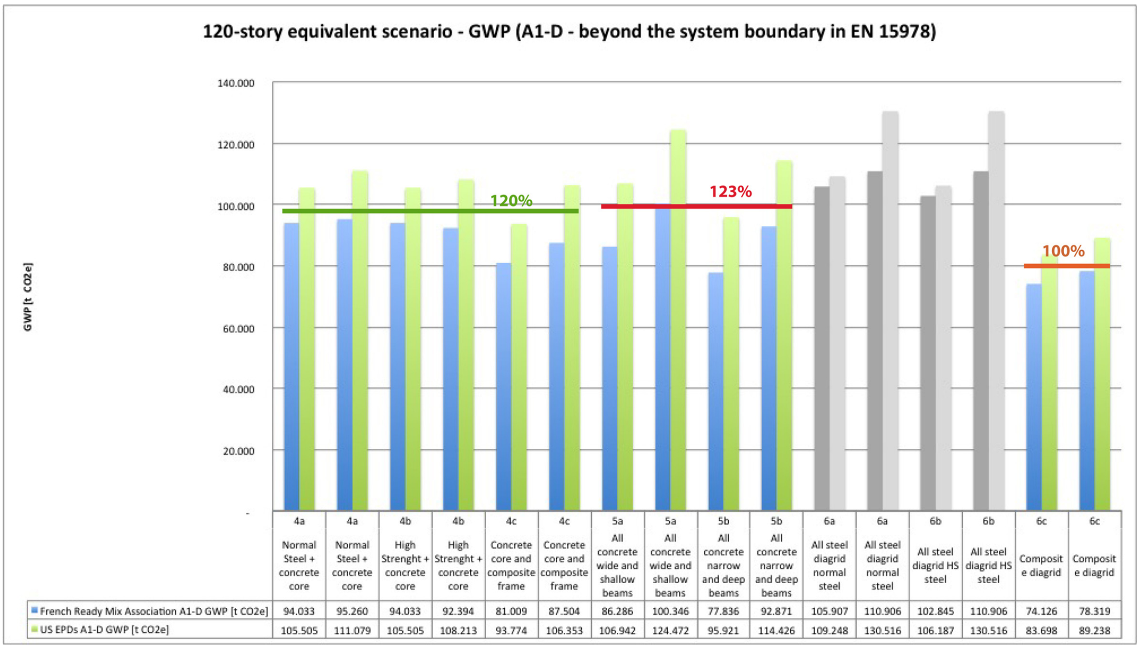

Figure 8. Graph 7: Results beyond the system boundaries as allowed by EN 15978. The structural solution for scenarios 6a and 6b (steel diagrid) proved to be unsuitable for a 120-meter tower. Source: CTBUH.

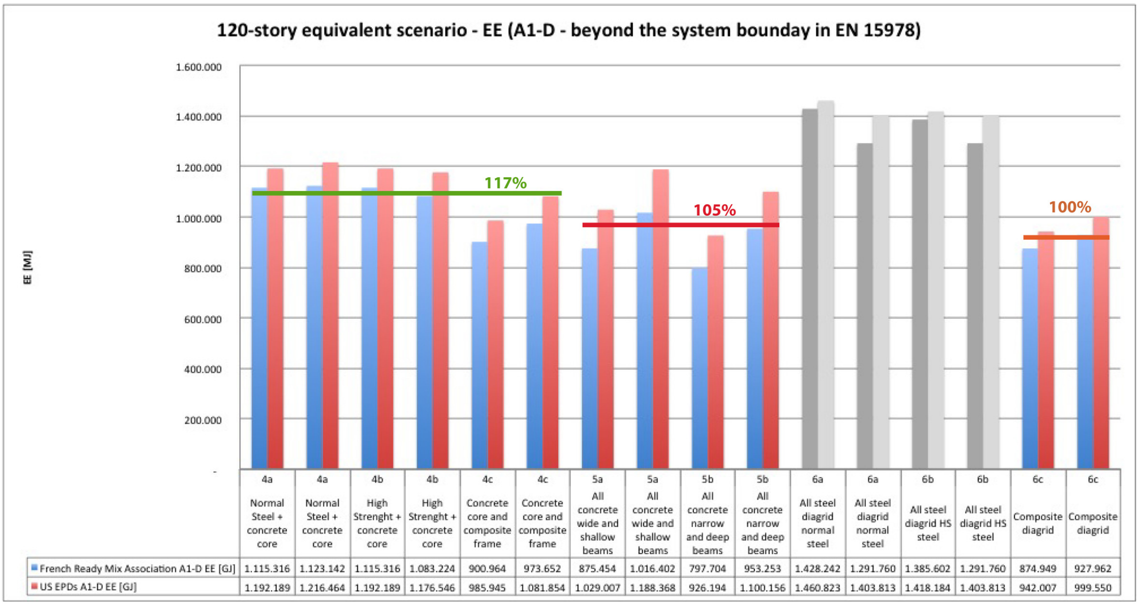

Figure 9. Graph 8: Results beyond the system boundaries as allowed by EN 15978. The structural solution for scenarios 6a and 6b (steel diagrid) proved to be unsuitable for a 120-meter tower. Source: CTBUH.

2 - The role of the building design team, consultants, and material supplier is fundamental to achieving a highly optimized structural system for a specific tall building. Also in this case, small decisions can have a major impact on the quantities of structural materials being used; their origin and functional properties have a big impact on the final environmental results.

3 - The impact categories and the indicators used (GWP and EE) are only two of the many ways that human actions affect the environment. Other dimensions can be considered when assessing the sustainability of buildings and building materials, such as the depletion of natural

Table 3. Credit from scrap: environmental benefits that can be obtained by recycling the materials. Supplementary information beyond the system boundaries. Source: CTBUH

LCA Phase:		Entire Life Cycle (Modules A1-C3)		Credit from Scrap (Module D)	
Short description	Scenario Number	GWP [t CO2eq]	EE [GJ]	GWP [t CO2eq]	EE [GJ]
Normal Steel + concrete core	1a	22,057	244,424	-3,836	-34,044
Normal Steel + concrete core	1a	19,194	216,702	-3,611	-32,043
High Strenght + concrete core	1b	21,902	242,404	-3,808	-33,797
High Strenght + concrete core	1b	18,831	211,972	-3,545	-31,463
Concrete core and composite frame	1c	21,564	235,764	-3,647	-32,365
Concrete core and composite frame	1c	18,766	209,916	-3,472	-30,812
All concrete wide and shallow beams	2a	21,592	207,121	-1,367	-12,129
All concrete wide and shallow beams	2a	27,298	279,177	-2,946	-26,140
All concrete narrow and deep beams	2b	18,988	185,091	-1,348	-11,958
All concrete narrow and deep beams	2b	23,147	238,914	-2,499	-22,180
All steel diagrid normal steel	3a	23,542	289,123	-4,914	-43,612
All steel diagrid normal steel	3a	21,812	266,519	-4,591	-40,739
All steel diagrid HS steel	3b	21,399	261,258	-4,524	-40,147
All steel diagrid HS steel	3b	21,115	257,472	-4,460	-39,582
Composite diagrid	3c	22,751	270,043	-4,423	-39,254
Composite diagrid	3c	19,453	225,903	-3,808	-33,795
Normal Steel + concrete core	4a	108,010	1,219,233	-17,299	-153,512
Normal Steel + concrete core	4a	109,405	1,227,723	-17,605	-156,226
High Strenght + concrete core	4b	108,010	1,219,233	-17,299	-153,512
High Strenght + concrete core	4b	105,912	1,182,238	-16,977	-150,655
Concrete core and composite frame	4c	90,417	961,564	-13,186	-117,013
Concrete core and composite frame	4c	97,642	1,039,256	-14,158	-125,645
All concrete wide and shallow beams	5a	87,190	847,854	-6,784	-60,199
All concrete wide and shallow beams	5a	101,714	988,060	-8,053	-71,461
All concrete narrow and deep beams	5b	79,525	782,172	-6,727	-59,695
All concrete narrow and deep beams	5b	95,435	940,617	-8,407	-74,606
All steel diagrid normal steel	6a	130,250	1,637,140	-25,521	-226,475
All steel diagrid normal steel	6a	125,222	1,393,478	-18,497	-164,146
All steel diagrid HS steel	6b	126,519	1,588,556	-24,850	-220,524
All steel diagrid HS steel	6b	125,222	1,393,478	-18,497	-164,146
Composite diagrid	6c	86,208	965,166	-14,888	-132,118
Composite diagrid	6c	90,375	1,017,568	-14,925	-132,450

resources or the amount of material waste at the end of a building's life.

4.2. Specific conclusion of the research

1 - After reviewing the results of the LCA analysis within the system boundaries of the EN 15978 (thus without considering the credit for scrap), the conclusions cannot be generalized for the two types of buildings. For the 60-story scenario, it can be pointed out that all concrete scenarios perform worse (as an average) than the other scenarios in terms of GWP while all steel scenarios are those with the highest EE. For the 120-story scenario, the discrepancies between the solutions are smaller with composite diagrid resulting the best solution from a GWP standpoint while all concrete scenarios have the lowest average EE.

2 - All scenarios might additionally benefit from the recyclability of the steel at the end of the building life cycle (steel sections and steel rebar). The EN 15978 imposed to be outside the system boundaries to have the possibility to account for the benefit of recycling steel scrap from the LCA results. Module D represents important *additional information* for the environmental accounting of various options (Table 3; Figs. 6~9; ATHENA, 2002).

Taking into account the recycling of material at the end of life clarifies the results. For the 60-story scenario, concrete solutions are those with the highest GWP and EE of all combinations, with mixed solutions (i.e., concrete core and steel or composite frame) resulting those with the lowest environmental impacts. Composite diagrid, on the contrary, result the best solutions for the 120-story building scenarios.

Table 4. Results of the environmentally optimized scenarios within the System boundaries as described by EN 15978. Source: CTBUH

Characterization factor source:		French Concrete		Environmentally optimized scenarios	
LCA Phase:		Entire Life Cycle (Modules A1-C3)		Entire Life Cycle (Modules A1-C3)	
Short description	Scenario Number	GWP [t CO2eq]	EE [GJ]	GWP [t CO2eq]	EE [GJ]
Normal Steel + concrete core	1a	22,057	244,424	-30%	-20%
Normal Steel + concrete core	1a	19,194	216,702	-32%	-20%
High Strenght + concrete core	1b	21,902	242,404	-30%	-20%
High Strenght + concrete core	1b	18,831	211,972	-32%	-20%
Concrete core and composite frame	1c	21,564	235,764	-28%	-19%
Concrete core and composite frame	1c	18,766	209,916	-30%	-19%
All concrete wide and shallow beams	2a	21,592	207,121	-13%	-13%
All concrete wide and shallow beams	2a	27,298	279,177	-23%	-21%
All concrete narrow and deep beams	2b	18,988	185,091	-15%	-15%
All concrete narrow and deep beams	2b	23,147	238,914	-23%	-21%
All steel diagrid normal steel	3a	23,542	289,123	-44%	-25%
All steel diagrid normal steel	3a	21,812	266,519	-43%	-25%
All steel diagrid HS steel	3b	21,399	261,258	-43%	-24%
All steel diagrid HS steel	3b	21,115	257,472	-43%	-24%
Composite diagrid	3c	22,751	270,043	-38%	-23%
Composite diagrid	3c	19,453	225,903	-34%	-21%
Normal Steel + concrete core	4a	108,010	1,219,233	-35%	-22%
Normal Steel + concrete core	4a	109,405	1,227,723	-34%	-23%
High Strenght + concrete core	4b	108,010	1,219,233	-35%	-22%
High Strenght + concrete core	4b	105,912	1,182,238	-33%	-22%
Concrete core and composite frame	4c	90,417	961,564	-27%	-19%
Concrete core and composite frame	4c	97,642	1,039,256	-27%	-19%
All concrete wide and shallow beams	5a	87,190	847,854	-16%	-16%
All concrete wide and shallow beams	5a	101,714	988,060	-17%	-16%
All concrete narrow and deep beams	5b	79,525	782,172	-18%	-17%
All concrete narrow and deep beams	5b	95,435	940,617	-18%	-18%
All steel diagrid normal steel	6a	130,250	1,637,140	-50%	-28%
All steel diagrid normal steel	6a	125,222	1,393,478	-32%	-22%
All steel diagrid HS steel	6b	126,519	1,588,556	-49%	-28%
All steel diagrid HS steel	6b	125,222	1,393,478	-32%	-22%
Composite diagrid	6c	86,208	965,166	-33%	-22%
Composite diagrid	6c	90,375	1,017,568	-34%	-22%

3 - Transportation of construction materials and demolition waste is not a very significant factor in a building LCA, with values typically ranging between 1~2.5% in terms of GWP and 0.9~3.2% in terms of EE. Consequently, if materials with better environmental performance are available, they can be transported across greater distances without a significant impact on the overall sustainability of the building structure.

4 - Horizontal structures (beams, floor slabs, etc.) represent 50~80% of the building weight on the shorter 60-story scenarios, while they represent 30~60% of the building weight in the taller 120-story scenarios. This ratio, and the consequent environmental impacts, can be reduced if shorter structural spans are used (the studied scenarios had 13.5 meters of unobstructed lease span) or lighter flooring systems are adopted.

5 - Significant environmental benefits can be obtained by choosing the proper material provider. A special set of characterization factors was used to run "environmentally-optimized" scenarios. In this set of environmental data, the best environmental properties of each material were used. Most of the steel products (steel profiles ASTM A913, rebar, etc.), for instance, can be purchased from electric arc furnaces, which use recycled steel scrap as their predominant material input. The environmental properties of such products are extremely beneficial, and the results of building structures designed with these materials have a GWP and EE significantly lower than the original structures designed with the average environmental values provided by WorldSteel (Table 4; WorldSteel Association,

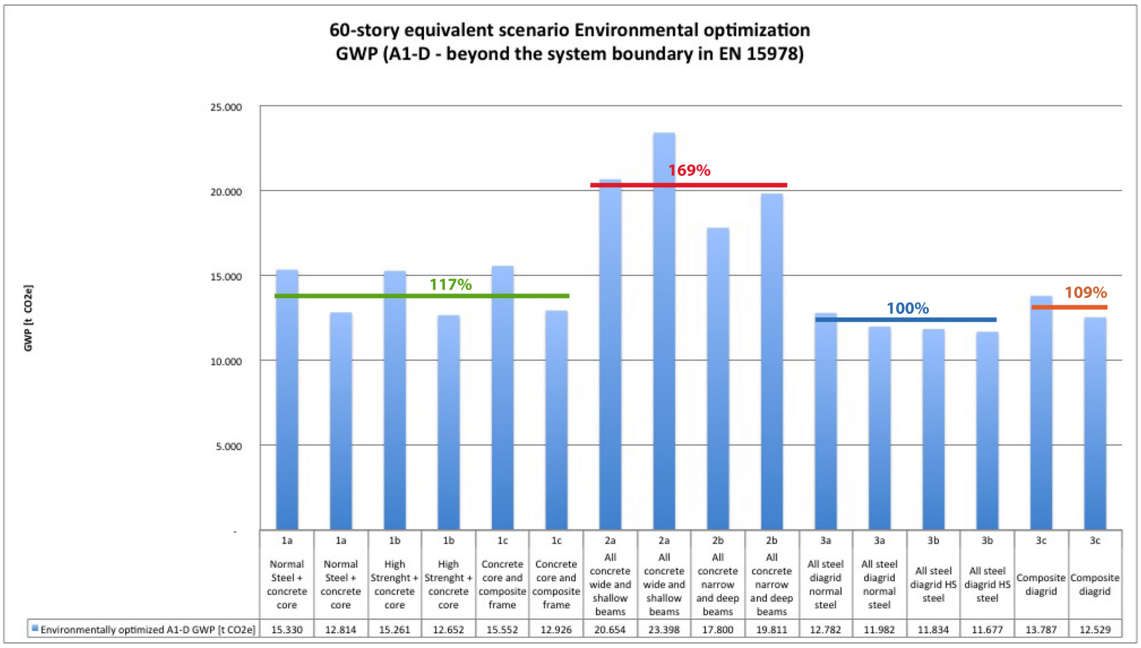

Figure 10. Graph 9: Results of the "environmentally optimized" 60-story scenarios for global warming potential, obtained by using the lowest characterization factors found in the literature for each steel product. Source: CTBUH.

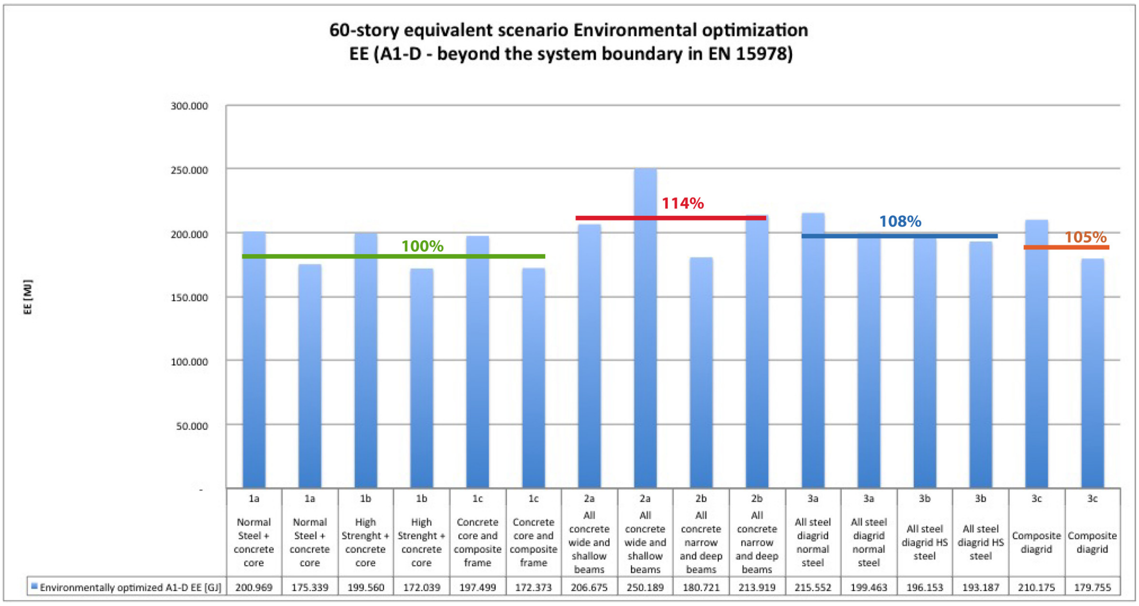

Figure 11. Graph 10: Results of the "Environmentally optimized" 60-story scenarios for embodied energy, obtained by using the lowest characterization factors found in the literature for each steel product. Source: CTBUH.

2011; Hammond & Jones, 2011; Figs. 10~13).

6 - Special design mixes of concrete can also be used to improve the environmental properties of structures. A significant percentage of cement in the mix can be substituted with other components such as fly ash, furnace slag, or silica fume, significantly decreasing the GWP and EE of the resulting concrete. However, concretes with cement substitutes have different behavioral properties than the corresponding "normal" concretes, such as longer curing times, possibly increased fragility, etc. As a result, these alternatives were not considered in the present research, despite the fact that they are being used in tall building

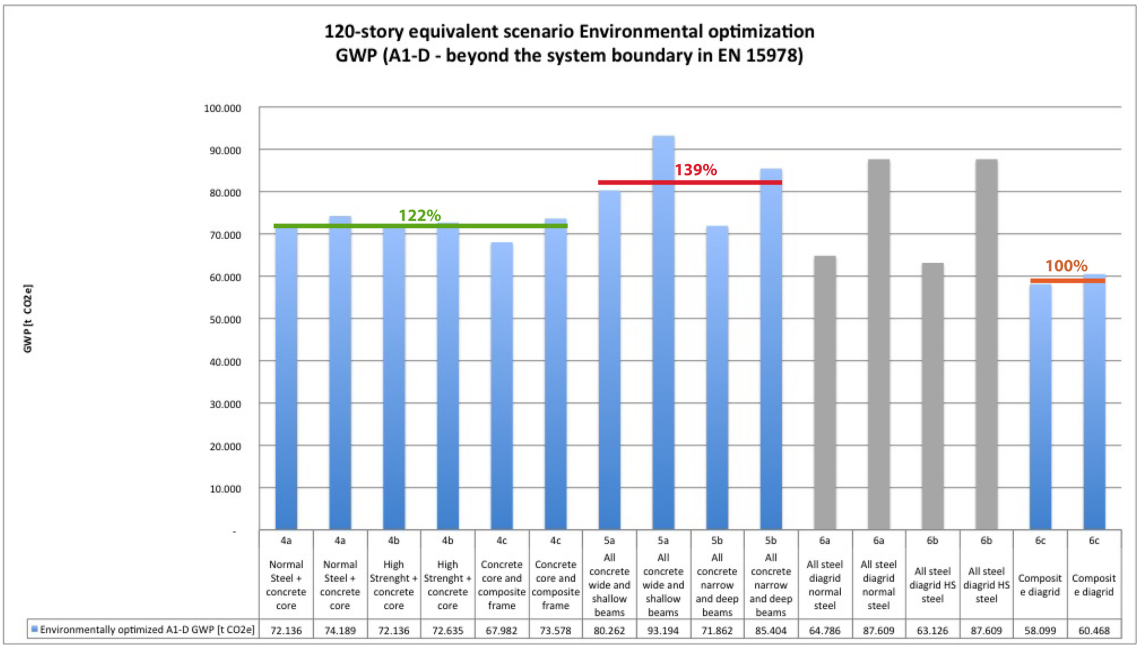

Figure 12. Graph 11: Results of the "environmentally optimized" 120-story scenarios for global warming potential, obtained by using the lowest characterization factors found in the literature for each steel product. The structural solution for scenarios 6a and 6b (steel diagrid) proved to be unsuitable for a 120-meter tower. Source: CTBUH.

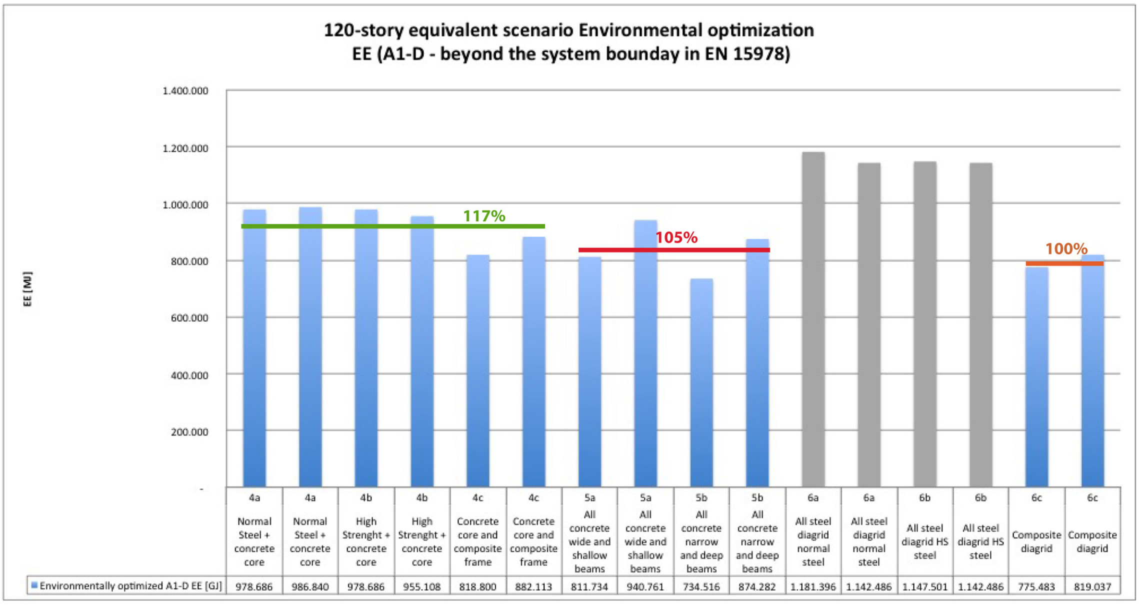

Figure 13. Graph 12: Results of the "environmentally optimized" 120-story scenarios for embodied energy, obtained by using the lowest characterization factors found in the literature for each steel product. The structural solution for scenarios 6a and 6b (steel diagrid) proved to be unsuitable for a 120-meter tower. Source: CTBUH.

construction when special characteristics are required (e.g., in hot climates, fly ash is used to reduce the heat of hydration when large quantities of concrete are poured) (Bentz et al., 2013; Fantilli & Chiaia, 2012).

5. Comparison with Literature Results

A small number LCA studies of tall buildings have been found in published literature, some authored by members

Table 5. Comparison with literature results. Source: CTBUH

Literature Sources							
Source	Assessment Method		Total Embodied Carbon [$kgCO_2/m^2$]	Embodied Carbon Structural Frame [$kgCO_2/m^2$]	Total Embodied Energy [GJ/m^2]	Embodied Energy Structural Frame [GJ/m^2]	Builindg Height
Foraboschi et al., 2014	Process Analysis	Steel frame + concrete core				3.15	40 story
						3.94	50 story
						3.77	60 stoty
		Concrete frame				2.2	40 story
						2.57	50 story
						2.46	60 story
Kofoworola and Gheewala, 2009	Process Analysis	Steel frame + concrete core			6.8	5,2*	38 story
Oldfield 2012	Process Analysis	Steel diagrid	955	340			40 story
Trabucco 2011	Input/Output	Steel diagrid			23.2		40 story
Trabucco 2012	Hybrid analysis	Concrete frame			15.7	4.23	40 story
Treloar et al. 2001	Input/output	Concrete core + composite column			18	11.7	42 story
		Steel frame + concrete core			18.4	11.6	52 story

* Data non explicitly indicated in the paper, extracted through interpretation.

CTBUH Research				
Short description	Scenario Number	GWP [$kgCO_2eq/sqm$]	EE [GJ]/sqm	Building height
Normal Steel + concrete core	1a	222	2.4	60
High Strenght + concrete core	1b	219	2.4	60
Concrete core and composite frame	1c	216	2.3	60
All concrete wide and shallow beams	2a	241	2.2	60
All concrete narrow and deep beams	2b	209	2.0	60
All steel diagrid normal steel	3a	243	3.0	60
All steel diagrid HS steel	3b	226	2.7	60
Composite diagrid	3c	228	2.6	60
Normal Steel + concrete core	4a	361	4.1	120
High Strenght + concrete core	4b	357	4.0	120
Concrete core and composite frame	4c	308	3.3	120
All concrete wide and shallow beams	5a	300	2.8	120
All concrete narrow and deep beams	5b	277	2.6	120
All steel diagrid normal steel	6a	431	5.2	120
All steel diagrid HS steel	6b	423	5.1	120
Composite diagrid	6c	292	3.3	120

of this research team. In order to perform a comparison with their findings, the results of the A1~A5 phase of this research have been divided by the gross floor area of the studied scenarios (141,600 square meters and 446,250 square meters for the short and tall scenarios respectively). A comparison table with the literature sources is offered in Table 5.

Only a few prior studies consider buildings of similar heights. In some circumstances, the results of these studies evidence GWP and EE values significantly lower than those found in the literature case studies, but the following explanation can be provided to justify the discrepancies.

The 60-story case studies of the research by Foraboschi (Foraboschi et al., 2014) are quite similar to the results of this study, and the discrepancy can be justified by a different building shape (square floor plan, 1:7 aspect ratio) and the different source of the characterization factors (Hammond & Jones, 2008).

The 52-story building considered by Treloar (Treloar et al., 2001) uses characterization factors derived from a fundamentally diverse methodology (input-output). Also, the structural elements of this building represent a remarkable ratio with the total embodied energy of the building, suggesting an underestimation of the other building components (curtain wall, interior finishes, MEP, etc.).

The concrete frame of a shorter 40-story building considered by Trabucco (Trabucco, 2012) has an EE value that doubles the results of this research, but the case study considered in that paper (Palazzo Lombardia in Milan) has a very peculiar shape. Additionally, a hybrid analysis (consisting in another different methodology) was used to extract the characterization factors of the building materials, thus the characterization factors for each material may vary significantly.

The GWP of the 40-story steel diagrid considered by Oldfied (Oldfield, 2012) is one and a half times higher than the 60-story diagrid considered in this research, but the building has a very iconic shape (30 st. Mary Axe, London) that might justify the discrepancy. Moreover, the study from Oldfield also includes the foundation quantities. The paper from Trabucco (Trabucco, 2011) on the same building has a remarkably different result from this research (with a much higher difference ratio from the results obtained by Oldfield), but an input-output method was used to obtain the characterization factors.

The above mentioned discrepancies attest to the critical issues related to the LCA methodology and the variability of the results mentioned in the first and second point of the general conclusion.

6. Ideas for Future Research Activities for the Tall Building Industry

Despite the above mentioned limitations with the general LCA methodology used for this study and its application, whose inconsistencies are being tackled by LCA experts worldwide, some aspects regarding the building industry in general and tall-buildings in particular can be investigated in future research activities as a result of the observations presented here.

An interesting field of research would be on the true profitability of long structural spans from a real estate perspective. Is there a true market premium for tall buildings with very long spans? Are there other aspects (e.g., environmental declarations and rating systems) that can compensate for the presence of more vertical structural elements, thus resulting in less materials being used for the horizontal beams and slabs?

Another field of research would be an investigation on innovative floor systems to be adopted in tall buildings that reduce the material quantities of the horizontal structures (floor beams, floor slabs, etc.).

From a broader perspective, fundamental research is needed to investigate the end-of-life of tall buildings. This important aspect of a building's life should be carefully assessed and planned for.

Eventually, an "end-of-life scenario" should be studied when a new building is proposed/designed so as to engage all interested parties (developer, designer, etc.) to make the right choices (material selection, construction method, use of prefabrication assembly, etc.).

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