LIFE CYCLE ASSESSMENT (LCA) OF A LEED-CERTIFIED GREEN BUILDING USING TWO DIFFERENT LCA TOOLS

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ABSTRACT

LIFE CYCLE ASSESSMENT (LCA) OF A LEED-CERTIFIED GREEN BUILDING USING TWO DIFFERENT LCA TOOLS

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In this study, Life Cycle Assessment (LCA) tool was used for analyzing the environmental effects of the green buildings associated with one of the world-wide used Green Building Rating Systems (GBRS) called Leadership in Energy and Environmental Design (LEED). The ultimate goal here is to contribute to the integration of LCA into LEED rating system. The secondary objectives were to execute several LCAs of both a hypothetical conventional building and an actual green building to compare the results of two different LCA softwares as One Click LCA and SimaPro and also to measure the level of sustainability of the actual green building. For the first purpose, LCA study was performed to a selected case study building having LEED v2009 Platinum certification by using two different LCA programs called One Click LCA and SimaPro. The system boundary was selected as A1, A2, A3, A4, B4, B5, C3 and C4 according to EN Standards. For the second objective, another LCA was performed in SimaPro for the case study building by taking a hypothetical conventional building as a reference. In this case, system boundary was determined as A1, A2, A3, A4, B1, B4, B6, B7, C2, C3, C4 and D. In both tasks, functional unit was set as “meter square of the building”. Impact categories of “Global Warming Potential (GWP)”, “Ozone Layer Depletion (OPD)”, “Acidification

Potential (AP)", "Eutrophication Potential (EP)", "Photochemical Ozone Formation Potential (POFP)" and "Abiotic Depletion Potential-Fossil Fuel (ADP-Fossil Fuel)" were considered. CML 2002 method was used in One Click LCA while CML IA Baseline was chosen in SimaPro. For the first objective, the results were only compared based on characterization values since One Click LCA does not give normalized results. Accordingly, results showed that One Click LCA and SimaPro showed highly comparable results in all impact categories except POFP and ADP-Fossil fuel due to the slight difference in system boundaries. In these impact categories, One Click LCA gives 58% and 32% higher results, respectively. For the second objective, environmental effects of the baseline building were found to be significantly higher than the case study building results in all impact categories. In both LCAs, natural gas, steel, concrete and aluminium cladding displayed significant impacts, commonly. However, huge discrepancies occurred in the results due to photovoltaic panels eliminating electricity use during operation together with the aluminium & PVC frame windows and recycling option in the disposal scenarios.

Keywords: Life Cycle Assessment, LEED, Green Building, One Click LCA, SimaPro

ÖZ

LEED YEŞİL BİNA SERTİFİKASYONLU BİNA İÇİN İKİ FARKLI YAZILIM İLE YAŞAM DÖNGÜSÜ ANALİZİ

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Bu çalışmada Yeşil Bina Değerlendirme Sistemleri'nin dünya çapında yaygın olarak kullanılanlarından biri olan Leadership in Energy and Environment (LEED) sistemi sertifikasına sahip olan binaların çevresel etkilerini analiz etmek için Yaşam Döngüsü Analizi (YDA) kullanılacaktır. Çalışmanın temel amacı YDA ve LEED uygulamalarının birbirine entegrasyonunu sağlamaktır. Çalışmanın ikincil amaçları ise One Click LCA ve SimaPro olmak üzere iki farklı YDA yazılımını karşılaştırmak ve bunun yanında konvensiyonel bir bina ile gerçek bir yeşil binanın YDA'larını yürüterek yeşil binanın sürdürülebilirlik seviyesini ölçmektir. Bunun için LEED v2009 Platin sertifikası almış örnek bir binaya bahsedilen farklı iki programda YDA uygulanmıştır. Bu kapsamda yürütülen çalışmada sistem sınırları EN Standartları'na göre A1, A2, A3, A4, B4, B5, C3 ve C4 olarak belirlenmiştir. Çalışmanın diğer amacı için ise seçilen binanın ve referans olarak oluşturulmuş konvensiyonel bir binanın YDA'ları yürütülmüş ve sonuçlar karşılaştırılmıştır. Bu kapsamda ise sistem sınırları EN Standartları'na göre A1, A2, A3, A4, B1, B4, B6, B7, C2, C3, C4 ve D olarak belirlenmiştir. Her iki amaç için yürütülen YDA'larda fonksiyonel birim bina metrekaresi olarak belirlenmiştir. Sonuçlar "Küresel Isınma Potansiyeli", "Ozon Tüketim Potansiyeli", "Asidifikasyon Potansiyeli", "Ötrofikasyon Potansiyeli", “Fotokimyasal Ozon Oluşturma Potansiyeli” ve “Kaynak Tüketimi Potansiyeli-Fosil Yakıtlar” etki kategorilerinde değerlendirilmiştir. One Click LCA programında CML 2002 etki metodu kullanılırken SimaPro’da yürütülen YDA’larda CML IA Baseline metodu dikkate alınmıştır. One Click LCA ve SimaPro karşılaştırmasından elde edilen sonuçlar, Fotokimyasal Ozon Oluşturma Potansiyeli ve Kaynak Tüketimi Potansiyeli-Fosil Yakıtlar etki kategorileri dışında program çıktılarının oldukça karşılaştırılabilir olduğunu göstermiştir. Bu etki kategorilerinde One Click LCA, SimaPro’ya göre sırasıyla %58 ve %32 olmak üzere daha yüksek sonuçlar vermiştir. Çalışmanın diğer amacında yönelik yürütülen analizlerde ise referans bina sonuçlarının tüm etki kategorilerinde gerçek binanın sonuçlarından oldukça fazla çıktığı görülmüştür. Yürütülen her iki analizde de ortak olan en yüksek sonuçların doğalgaz, çelik, beton ve alüminyum cephe kaplamasından kaynaklandığı görülmüştür. İki analizde görülen büyük farkların ise gerçek binada elektrik tüketimine sıfıra indiren fotovoltaik paneller ile alüminyum & PVC pencere seçimleri olduğu görülmüştür. Yıkım sonrası gerçekleştirilecek geri dönüşüm aktivitelerinin de sonuçları önemli ölçüde etkilediği tespit edilmiştir.

Anahtar Kelimeler: Yaşam Döngüsü Analizi, LEED, Yeşil Bina, One Click LCA, SimaPro

To my lovely and encouraging family

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AD: Abiotic Depletion

ADP: Abiotic Depletion Potential

AP: Acidification Potential

AoPs: Areas of Protection

BREEAM: Building Research Establishment's Environmental Assessment Method

CASEBEE: Comprehensive Assessment System for Building Environmental Efficiency

DQI: Data Quality Indicator

ED: Eutrophication Potential

EN: European Standards

EP: Eutrophication Potential

EPA: Environmental Protection Agency

EPD: Environmental Product Declaration

GBRS: Green Building Rating System

GHG: Green House Gas

GNP: Gross National Product

GWP: Global Warming Potential

IFC: Industry Foundation Class

ISO: International Organization for Standardization

KPI: Key Performance Indicators

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LEED: Leadership in Energy and Environmental Design

ODP: Ozone Depletion Potential

POFP: Photochemical Ozone Formation Potential

PVC: Poly Vinyl Chloride

SETAC: Society of Environmental Toxicology and Chemistry

SLCA: Social Life Cycle Assessment

UNEP: United Nations Environmental Programme

USGBC: United States Green Building Council

XPS: Extruded Polystyrene

VAV: Variable Air Volume

VRF: Variable Refrigerant Flow

VOC: Volatile Organic Compound

CHAPTER 1

INTRODUCTION

1.1. General

The built environment has many significant impacts on natural environment, economy, health and productivity. These effects can start from the initial work on site and end with the demolition and final disposal of the building materials. From the environmental point of view, these effects can reach serious limits in many cases. According to European Commission (2014), construction sector accounts for about half of raw materials and energy consumption and also one third of water consumption. Additionally, it is responsible for one third of all waste generated (European Commission, 2014). Consequently, "sustainable construction" term has been developed in years in order to reduce detrimental effects of construction sector. At this point, "sustainable development" concept should be better known in order to understand the principles of sustainable construction.

Most popular definition of "sustainable development" was released in the Brundtland Report –also known as "Our Common Future"- in October 1987. In this report, sustainable development is defined as below:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."(United Nations, 1987)

Due to the fact that "sustainability" has different meanings in many contexts, it has a lot of uncertainty about what it really means (Sfakianaki, 2015). Naturally, sustainability is a composition of several roots like environmentalism, conservationism and social justice. However, all of them was harmonized under the name of "sustainability" by the end of the 20^{th} century. Although today sustainability is mostly used for environmental issues, it has two other pillars as society and economy (University of Alberta, n.d.). On this basis, sustainable construction relies on these triple bottom line of sustainable development in an integrated manner. Particularly, a "sustainable building" may be defined as a building having implementations by considering environmental, economic and social performance. It also involves the functional quality and occupant comfort, so it gains attention in today's occupancy and market trends. However, these trends are highly related to the construction market and building stock. Due to the fact that construction market is almost saturated in many parts of the world and interest for high-quality buildings increases, new policies and incentives have been getting applicable in the last few years (Hui, 2002). Green Building Rating Systems (GBRS) are one of the sustainable construction tools getting more and more common all over the world. Although most of the GBRS applications are not governmentally mandatory yet and valid through volunteering actions in many places, the legal bindings, relevant standards and incentives are expected to be more common in coming years. According to UNEP (2011) report, it is estimated that green building sector economy will reach 1-trillon dollars until 2050 and energy used in construction sector will decrease by one third ratio due to the expected raise in the number of green buildings (Yılmaz & Bakış, 2015).

Although there are quite few definitions about green buildings, World Green Building Council defines "green building" as a building that reduces or eliminates negative impacts on the environment, preserves natural resources and increases the quality of life during its design, construction and operation periods (World Green Building Council, 2019). However, this term is not as basic as it is defined since different regions have distinct natural, economic and cultural characteristics. These features may modify the definition of a green building depending on the local properties such as climate, cultural background or economic trends. Yet, it is a useful concept to achieve sustainable construction goals starting from local, proceeding with regional and ending with global sustainability targets.

On the other hand, one of the considerations in green building design is to manage resource use and to choose sustainable materials by looking at their green specifications such as their embodied energies, durability, recycled contents, waste minimizations and their ability to be reused or recycled (Patel & Chugan, 2013). According to European Commission (2014), there are several strategies that can be used to decrease the consumption of resources and related environmental impacts of the life cycle of a building:

- Better project planning assuring the use of energy efficient and environmental friendly products, majorly
- Encouraging the products that are manufactured via sustainable paths such as recycled products
- Promoting reduction of construction waste that is sent to the landfills (European Commission, 2014)

At this juncture, Life Cycle Assessment (LCA) can be considered as one of the most prevalent tool to assess the impacts of a material or process on the environment during its whole life-cycle. Therefore, it poses a key role in both design and construction phase of green buildings where material selection and the decision of building systems are done. Consequently, integration of LCA into green building applications has gained more importance in recent years and keeps going its own development via various sectoral projects and academic studies.

One critical problem realized while doing literature review is that there are not much details given for the research processes in the published studies. Moreover, the results are only given by figures rather than numerical representations which explains the results superficially and poses a difficulty in reaching a totally understandable conclusion. Therefore, this study tries to provide a more clear inventory and also more explicable results by giving exact numerical values.

There are a number of studies conducted so far regarding LCA-based comparison of different building types in the literature. However, both green building applications and LCA concept are quite new in Turkey and therefore there are limited number of studies conducted on those topics. With the help of this study, it is expected that a clear example of the sustainability degree of a certified green building in Turkey will be represented in the literature regarding particular properties of the country. Additionally, there are also studies comparing different kind of LCA softwares especially the ones having common use and validation in the field like SimaPro and GaBi. However, it was found that One Click LCA which is a new and building-oriented LCA program was not analyzed and compared to the other LCA softwares yet. Therefore, the analysis of the comparison of the results of One Click LCA and SimaPro will provide a new perspective for the LCA practitioners while they try to decide which program to be used according to their goal.

1.2. Objective and Scope of the Study

Although a building is designed according to sustainable architecture principles, it may not be really "green" in many cases. The question of "How much is the building green?" is still a difficult question to be answered in such cases. Determining satisfaction levels of green properties is often a qualitative procedure. However, LCA helps people to quantify the impacts of green strategies via comparison of green and conventional buildings by also covering post-occupancy period. On the other hand, the softwares used for quantification of environmental impacts may give different results making LCA process less accurate and open to debate. Considering all these questionable issues, this study has two objectives as;

- Examining the results of two different LCA softwares in order to find discrepancies and the issues that can be developed
- Comparing a conventional building and a LEED certified green building in terms of their material and operational water and energy uses to assess how much the case study building is green

To do these, a LEED Platinum certified office building located in Ankara, Turkey was selected. The building was assessed in two different LCA programs as One

Click LCA and SimaPro. In this case, system boundaries were selected according to the purchased One Click LCA version. Thus, Raw Material Supply (A1), Transport (A2), Manufacturing (A3), Transport to Building Site (A4), Replacement (B4), Refurbishment (B5), Waste Processing (C3) and Disposal (C4) steps were included in both LCAs. However, B5 stage was not taken into account due to lack of data when the case study building was assessed in SimaPro. Functional unit was chosen as 1 m^2 of the floor area and CML 2002 impact method was used in both softwares.

For the second objective, the case study building and a conventional office building were compared. The analysis consists of main building elements and operational water and energy use. A hypothetical baseline building having the same area, orientation and location was created by considering conventional office building properties in Turkey. The two LCAs were conducted in SimaPro 8.4.1.0. Boundaries were chosen according to the stages defined by European Standards (EN) and includes Raw Material Supply (A1), Transport (A2), Manufacturing (A3), Transport to Building Site (A4), Use/Application (B1), Replacement (B4), Operational Energy Use (B6), Operational Water Use (B7), Demolition Waste Transport (C2), Waste Processing (C3), Disposal (C4) and Reuse/Recovery/ Recycling (D) steps. The functional unit was determined as 1 m^2 of floor area. For the impact assessment method, CML IA baseline method was used.

CHAPTER 2

LITERATURE REVIEW

2.1. Green Building Rating Systems

As the adverse impacts of construction sector had become more apparent in 1970s, the emphasis on sustainable design increased. Thus, a new approach which promotes standardization in construction activities was developed. Since then, marketable Green Building Rating Systems help designers, architectures and engineers in measuring how much sustainable these buildings are. The main logic behind almost all GBRSs is to assess the degree of sustainability of the buildings by setting various criteria and giving points to the projects depending on the compliance to these criteria (Altın, 2016).

The first green building rating system was developed under the name of “Building Research Establishment’s Environmental Assessment Method (BREEAM)” in the U.K. in 1990. It is known as a pioneer since it addressed an enhanced understanding of environmental and sustainability issues for the first time. Following this, U.S. Green Building Council (USGBC) established another rating system named “Leadership in Energy and Environmental Design (LEED)” in 2000. On the other hand, ECD Energy and Environmental Canada developed Green Globes certification system for existing buildings in the same year (“About Green Globes,” n.d.). After one year of the establishment of LEED and Green Globe, a corporation consisting of industry, government, academia and Japanese Ministry of Land, Infrastructure and Transport released a new GBRS called “Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)” in 2001. This trend continued until China’s own GBRS called GBAS (2006), German Sustainable Building Council’s DGNB (2007) and United Arab Emirates’ ESTIDAMA (2008) had released (Mohd et al., 2018). The pace in generating new GBRSs and enhancing the existing ones is still fast all over the world. In this context, many countries try to establish their own certification systems besides using commonly accepted GRBSs in the world. A brief summary of GBRSs that are administrated by World Green Building Council is demonstrated in Table 2.1. There are also a number of GBRSs that are not administrated by World Green Building Council.

Table 2.1. *Green building rating systems administrated by World Green Building Council (World Green Building Council, 2019)*

ARZ Rating System	Green Building Index	LOTUS
BERDE	Green Key	Miljöbyggnad
BREEAM	Greenship	NABERSNZ
Casa	GreenSL	OMIR
CASBEE	Green Star	Parksmart
CEDBIK	GRESB	PEARL
Citylab	Home Performance Index	PEER
DGNB	Homestar	PGBC
DGNB Woonmerk	HQE	Singapore Green Building
EDGE	ICP	SITES
GBC Brasil Casa	IGBC	TARSHEED
GBC Home	INSIDE/INSIDE	The Well Building Standard
GBC Quartieri	Korea Green Building Certification	VERDE
GreenBuilding	LEED	Zero Waste

Most of the GBRSs have similar properties in common and are differentiated from each other by slight variations. The reason behind the similarities is caused by the fact that the main goal of all GRBSs is to promote sustainability in construction sector. Eventually, the principles are mostly based on the same approaches. Almost all GRBSs aim to decrease water and energy uses of the buildings, encourage the use of renewable energy and alternative sources, emphasize the importance of embodied energy and improve the occupant comfort and well-being, in common.

On the other hand, content of the GBRSs may change according to the local features like geography, climate and cultural aspects and also the type of the building. In this case, a particular system can give more weight to the issue that is more critical for the relevant area. To illustrate, CASBEE has a strong emphasis on the land use since it is originated from Japan which is an island country while The Pearl Rating System for Estidama mostly tries to develop water efficiency due to the water scarcity in the Middle East. Moreover, governmental and legal regulations may affect the content of the certification system.

Although variety of GBRSs provide an enhanced scale of choice, it may also pose a disadvantage in some countries where multiple GBRSs are applicable. In this case, confusions may appear in the mind of stakeholders while selecting the proper certification system. Turkey is a good example for this circumstance. Although LEED and BREEAM are the most preferred rating systems is Turkey, several other GBRSs have been developed in years such as B.E.S.T Home Certification launched by CEDBIK and Safe – Green Building Certification released by Turkish Standards Institute. Therefore, a unification or harmonization of the systems may be beneficial in order to prevent confusion when selecting proper GRBS for a particular project.

2.1.1. Leadership in Energy and Environmental Design (LEED)

After the establishment of USGBC in 1993, a committee in the council decided to create a green building rating system that building industry needs. The committee was formed of a wide range of people coming from different disciplines like architects, real estate agents, a building owner, a lawyer, an environmentalist and industry representatives. This diversity in the team helped to establish a comprehensive rating system, ultimately.

The first LEED Pilot Project Program which is also referred as LEED Version 1.0 was released in August 1998. The next version was launched under the name of LEED Green Building Rating System Version 2.0 in March 2000 followed by LEED Version 2.1 in 2002, LEED Version 2.2 in 2005, Version 3.0 in 2009 and Version 4 in 2016. Since LEED is open to changes, modifications and new ideas, the rating system has evolved in time resulting in a more up-to-date measurement criterion. Each project should comply with the current version requirements at the time it is registered (LEED, 2009).

LEED is a credit system that is voluntarily applied, consensus-based and market-driven. It evaluates the buildings' environmental performance from an extensive point of view according to particular standards. In other words, it helps defining, implementing and estimating green building and neighborhood design, construction, operation and maintenance in an integrated way. It also promotes design practices, raise consumer awareness and eventually transforms the building market (Hoff, 2007).

Instead of presenting a complex definition of "green building", LEED prefers a more simple definition by emphasizing its most significant features such as water and energy efficiency, atmospheric impacts, sustainable materials, indoor environmental quality, etc. (Hoff, 2007). In other words, it is a rating system which combines those basic principles via a holistic approach. LEED has seven fundamental goals to promote guidance for a better construction options:

- To diminish the effects of climate change
- To promote the human health
- To protect and restore water resources
- To enhance biodiversity
- To encourage sustainable material resources

- To build a greener economy
- To improve social equity, community health and quality of life (U.S. Green Building Council, 2013).

In order to achieve goals mentioned above, LEED v4 BD + C has six major categories having their own requirements. Under each of these categories, there are mandatory and optional strategies. While mandatory strategies are named as “prerequisites”, optional alternatives are called as “credits”. Main categories are listed as;

- Location and Transportation (LT)
- Sustainable Sites (SS)
- Water Efficiency (WE)
- Energy and Atmosphere (EA)
- Material and Resources (MR)
- Indoor Environmental Quality (IEQ) (Owens et al., 2013)

Besides, project teams can also earn points from Innovation and Regional Priority categories.

LEED has several rating system adaptations depending on the type of the building. These are classified depending on whether the building is used commercial, institutional or residential purpose and should be selected, accordingly. Each adapted version has its own prerequisites and credits that are primarily the basis of LEED goals above. Each credit is weighted according to their contribution to the goals. The ones contribute to the most important goals have more weight than the others. Project team should first achieve each prerequisite so that they can also apply for the credits under each category. At the end, project can earn four level of certification which are Certified (40-49 points), Silver (50-59 points), Gold (60-79 points) and Platinum (80+ points) depending on the point achieved.

Rating system adaptations are tabulated in Table 2.2:

Table 2.2. *Rating system adaptations in LEED (“Selecting a LEED rating system,” 2019)*

Green Building Design & Construction (BD + C)
LEED BD + C: New Construction and Major Renovation
LEED BD + C: Core and Shell Development
LEED BD + C: Schools
LEED BD + C: Retail
LEED BD + C: Data Centers
LEED BD + C: Warehouses and Distribution Centers
LEED BD + C: Hospitality
LEED BD + C: Healthcare
LEED BD + C: Homes and Multifamily Lowrise
LEED BD + C: Multifamily Midrise
Green Interior Design & Construction (ID + C)
ID + C: Commercial Interiors
ID + C: Retail
ID + C: Hospitality
Green Building Operations and Maintenance (O + M)
O + M: Existing Building
O + M: Retail
O + M: School
O + M: Hospitality
O + M: Data Centers
O + M: Warehouse and Distribution Centers
O + M: Multifamily
Green Neighborhood Development (ND)
LEED ND: Plan
LEED ND: Built project

Alike all green building rating systems, LEED has both advantages and disadvantages. Advantages can be listed as follows:

- It offers a broad range of sustainability elements including not only minor issues in construction sector but also a comprehensive context.
- It implements a simple and understandable approach that can be easily implemented by both designers and construction professionals. It prefers to

apply simple and consensus-based point system rather than sophisticated computer models.

- In addition to its simplicity and comprehensiveness, LEED also appeals the competitive nature of the society. A LEED certification can be regarded as an indication of the effort of the building owners and designers to make the building more sustainable. Eventually, it drives a competition in the market through implementing a more sustainable policies in the construction sector by offering a straightforward benchmarking system (Hoff, 2007).

On the other hand, LEED also poses several disadvantages mentioned below:

- It is relatively expensive for individual homeowners and small commercial buildings.
- It does not consider the performance period of the building after certification. It is a very vital issue in life-long sustainability results of the building since LEED does not guarantee the good performance of the building in the operation period.
- It does not encourage the innovative approaches applied in the building. The building may not reach the target point and certification level although there is a new and innovative design element implemented to the project. Therefore, it may create a tendency to choose easily achievable credits rather than presenting a new approach (Avastthi, 2013).

Among all other GBRSs, LEED rating system was selected for this study since it is the most preferred rating system in Turkey. In Turkey, classical construction perception which ignores demand of consumers has started to change in recent years. By the increased awareness in energy and environmental-friendly product sectors, up-to-date and internationally accepted construction strategies have been spread over the country. Consequentially, the existing legal infrastructure have started to be updated and revised as parallel to the global market (Yılmaz & Bakış, 2015). Although LEED is a voluntary certification program, the effect of raising awareness and legal improvements promotes LEED implementations in Turkey. According to 2018 data released by USGBC, Turkey is ranked as 6th country in the world where there are the highest square meters of LEED projects conducted. Table 2.3 represents top ten countries having highest number of LEED projects.

Table 2.3. *Statistics of the LEED projects all over the world (Stanley, 2019)*

Ranking Country / Region	Number of Projects	Gross Square Meters (millions)
1. Mainland China	1,494	68.83
2. Canada	3,254	46.81
3. India	899	24.81
4. Brazil	531	16.74
5. Republic Korea	143	12.15
6. Turkey	337	10.90
7. Germany	327	8.47
8. Mexico	370	8.41
9. China, Taiwan	144	7.30
10. Spain	299	5.81
United States*	33,632	441.60
*The United States, where LEED originated, is not included in the list, but remains the world's largest market for LEED.		

2.1.1.1. Importance of Water and Energy Analysis in LEED v4

As the main target of all GRBSs, LEED aims to create a foundation to push building industry toward a more sustainable alternatives. It provides various quantification methods for water and energy efficiency, indoor air quality or building material selection. While these quantification methods are generated as a credit system, the point allocation process is used for weighing. In other words, LEED establishes a simplified system to a more complex issue which basically requires a detailed and correct share of all subjects considered within the present rating system (Owens et al., 2013).

In early versions of LEED, credit weights were determined by the members of Technical Advisory Committees. However, allocation points were based on professional judgements in this approach. Thus, in LEED v2009 a new weighing system was developed in order to serve a more comprehensive strategy for all credits depending on their effect on environmental problems. This path extends the allocation system toward an analytical based version focusing on building performance. The impact categories of the system were derived from the Environmental Protection Agency's TRACI categories which are used for LCAs. At the end of the modifications, allocation process of LEED v2009 has become a system including caused environmental problems and human health issues.

In the following years, LEED v4 adopted previously developed weighing system of LEED v2009 and added new criteria for the whole built environment. The LEED Steering Committee tried to address new impact categories focusing on LEED's environmental, social and economic goals rather than just concentrating on environmental problems. At this point, a new way of thinking was developed that promotes questioning of the ultimate accomplishment of a LEED project. In addition to adding new impact categories, LEED v4 also found a web-based, statistical tool that measures multivariate connections between strategies and impacts. The main advantage of this tool is to provide a better understanding of the behavior of the system while LEED goals are met.

Briefly, points are allocated through a weighing process and the point of a specific credit is determined according to the relative effectiveness of it to the accomplishment of the goals. In other words, a credit having more contribution to the goals gets more point. This basic concept uses a multi-criteria analysis approach in which expected outcome of each credit on the impact categories is evaluated. Figure 2.1 illustrates how the impact categories are used to analyze the credits.

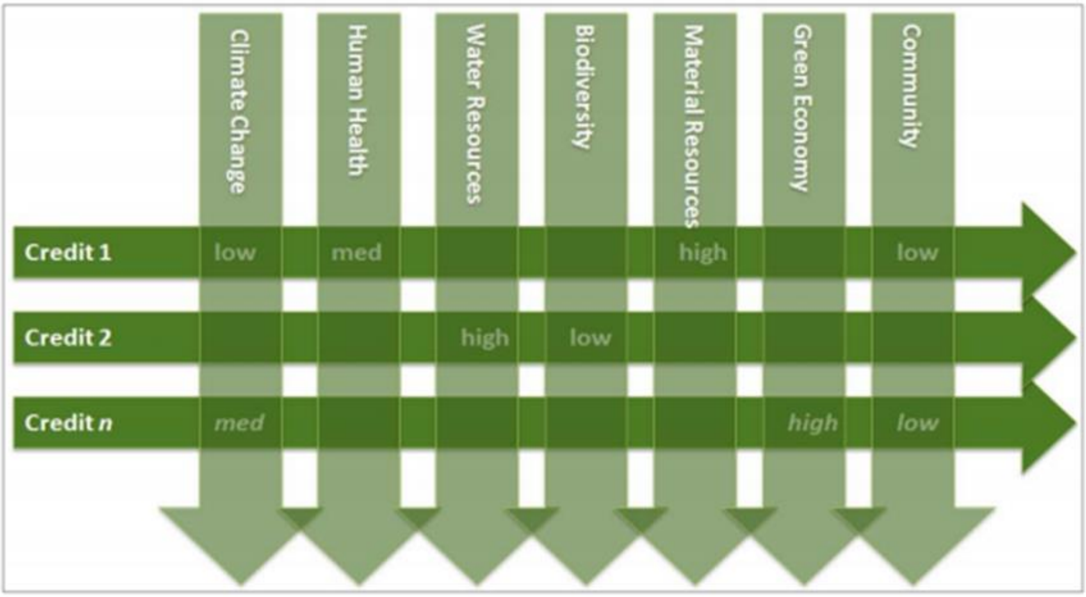

Figure 2.1. Demonstration of weighing LEED credits (Owens et al., 2013)

As it can be seen from Figure 2.1, credits and impacts categories are demonstrated in the rows and columns together with the relevant associations in the cells in between. Each cell represents strength of the associations between credits and impact categories. Moreover, each impact category is weighted depending on their importance compared to the other ones. These weights are combined with the related associations and then normalized to obtain a final score of 100 point. A cell with “0” point indicates that there is no solid relation between the credit outcome and impact category. A simplified illustration of the weighing process is shown in Table 2.4.

Table 2.4. *Weighing of impact categories (Owens et al., 2013)*

Impact Category Weight >>	50%	25%	25%
	Impact Category- Climate Change	Impact Category – Human Health	Impact Category – Water Resources
Credit 1	65	0	0
Credit 2	10	50	20
Credit 3	10	15	75
Credit 4	15	35	5
	100	100	100

Weighing procedure of impact categories is a different process since partial shares of each impact category is determined by a consensus. To illustrate, a serious global problem like Climate Change is given higher weight than the other impact categories. Similarly, impact categories having less certain or less severe effects are given less weights out of 100. Weighing of the LEED v4 impact categories is shown in Figure 2.2.

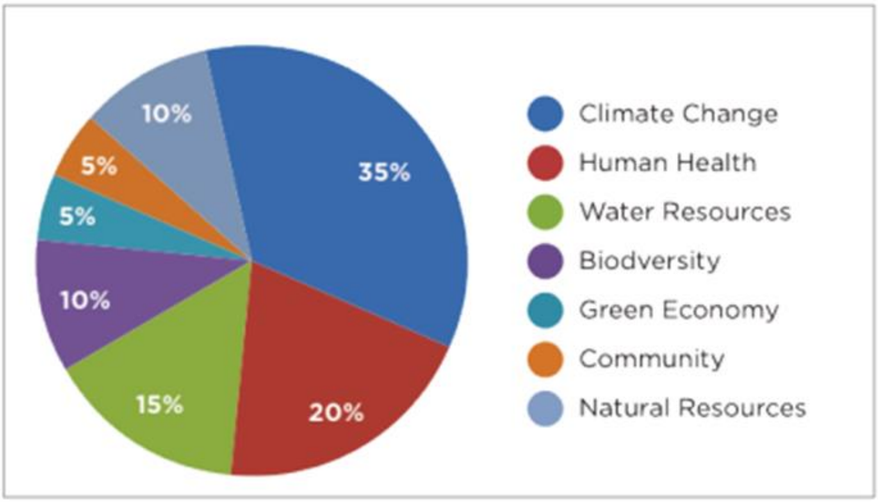

Figure 2.2. Weighing of LEED V4 impact categories (Owens et al., 2013)

At the end of the point allocation process, a scorecard showing all credits and attained points was developed. Accordingly, it is seen that Water Efficiency and Energy and Atmosphere categories gain 44 points over 110 in BD+C rating system. Besides, there are several other points coming from different credits that have secondary and/or indirect relations with the water and energy efficiency of the project. Therefore, water and energy analysis is also included together with the embodied energy analysis in this study to have a better understanding of building life cycle.

2.2. Life Cycle Assessment (LCA)

Life Cycle Analysis (LCA) is a quantitative tool for the assessment of the environmental impact of a product, a process or an activity through its whole life cycle. The primary objective of the assessment is to reduce the environmental impact of the product by guiding the decision-making process towards more sustainable solutions (Stranddorf et al., 2005).

The term “life cycle” means the essential periods in the course of the product’s life span, starting from the raw material extraction to final disposal by including manufacturing, use, maintenance and end of life stages. At this point, LCA acts as a minimizer reducing the impacts at one stage while helping to avoid an increase in any other stages within the life span by avoiding shifting burdens, i.e. by not causing any increase in another stage (Stranddorf et al., 2005).

Historically, LCA studies initialized in the late 1960’s and early 1970’s. These studies mainly focused on energy analyses but then the limits of study areas enhanced into the resource requirements, emission loadings and generated waste. At this period, LCA’s were primarily conducted on packaging alternatives. When it comes to early 1980’s, a rapid growth in LCA studies was observed. It is also the same time when the first impact assessment method was released. Briefly, the period between 1960 and 1990 was the time span in which a wide range of LCA concepts, terminologies and methods were discussed. Due to the lack of a common theoretical framework, the strategies were performed in various ways resulting in quite different outcomes (Guinée, n.d.).

LCA concept became more theoretical and applicable in the 1990s by the help of world-wide scientific coordinations. Society of Environmental Toxicology and Chemistry (SETAC) and International Organization for Standardization (ISO) started to organize workshops and prepared guidelines on LCA. During this period, LCA also became a part of policy document and legislation. Additionally, the methods and concepts still used today were evolved in this period such as definition and use of endpoint and damage approaches, potential human and ecotoxic emissions. All in all, the years between 1990 and 2000 was the time of founding LCA on scientific disciplines and standardization of LCA.

In the first decade of 21th century can be called as decade of elaboration since there was an increasing attention to LCA concept. The United Nations Environmental Programme (UNEP) and SETAC released an International Life Cycle Partnership, also known as Life Cycle Initiative, in 2002. The major target of the initiative was to develop practices according to a formulated structure and also improve supporting tools. The decade including 2000-2010 comprised of divergence of methods because ISO never standardize LCA methods in detail and they all open to different interpretations with respect to system boundaries, allocation methods, etc. Nevertheless, first Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) ideas were proposed in this period (Guinée, n.d.). Since then, LCA studies have been increased and keeps its pace until today.

As mentioned above, ISO has published a set of guidelines for LCA in order to shape a more structured and internationally-accepted method. These guidelines are;

- ISO 14040 - Principles and framework (2006)
- ISO 14041 - Goal and scope definition and inventory analysis (1998) – not in use
- ISO 14042 - Life cycle impact assessment (2000) – not in use
- ISO 14043 - Life cycle interpretation (2000) – not in use
- ISO 14044 – Requirements and guidelines (2006)

- ISO 14047 – Illustrative examples on how to apply ISO 14044 to impact assessment situations (2012)
- ISO 14048 – Data documentation format (2002)
- ISO 14049 – Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis (2012) (Menoufi, 2011)

Among all of the standards stated above, ISO 14041, ISO 14042 and ISO 14043 are revised and included by ISO 14040:2006. According to the International Standard 14040:2006, LCA is defined as a technique for assessing the environmental aspects and potential impacts associated with a product by compiling and inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs and interpreting the results of the inventory analysis and impact assessment phases in relation to the objective of the study (UNEP, 2003). This is done by 4 main steps as Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation, which are also demonstrated in Figure 2.3. Double arrows indicate the interactive and iterative structure of the process. In other words, LCA is open and flexible for any change in the steps if there is a missing information, unclear results or inconsistency between the results and the scope. Figure 2.3 shows LCA steps defined by ISO 14040.

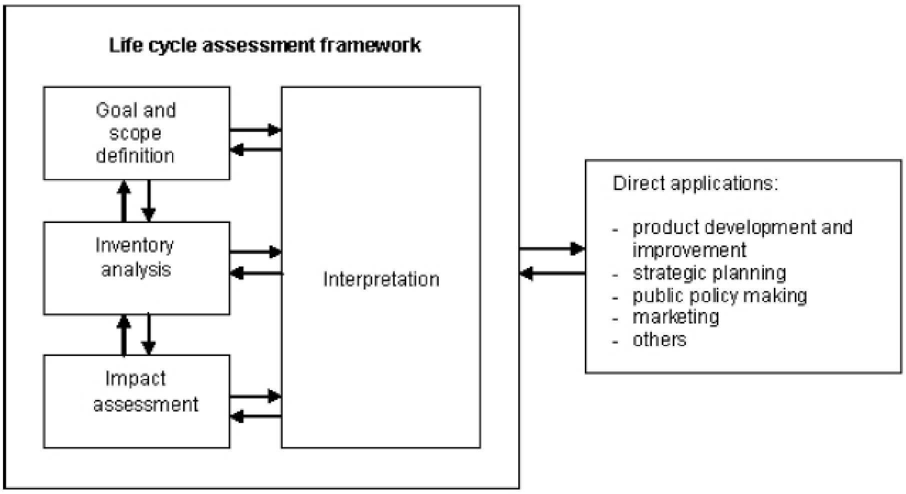

Figure 2.3. LCA steps according to ISO 14040 standard (Menoufi, 2011)

Goal and Scope Definition

Goal and scope definition phase is the first and essential step that has a significant effect on the whole LCA process. Since LCA practitioners create a model while conducting a life cycle analysis, there should be some boundaries and simplifications in order to demonstrate relevant complex system in their model, properly. This demonstration should be structured in a way that the simplifications and distortions do not influence the results too much (Goedkoop et al., 2016). Therefore, goal and scope definition stage is a vital step that maintains the consistency between the aim of analysis and the result obtained. Although the practitioner should define the goal and scope clearly in order to make true decisions throughout the study, he/she may need to modify them according to the additional changes during analysis period caused by the iterative nature of the LCA.

Goal and scope definition step should include:

- The reason for conducting an LCA and the questions to be answered including intended use of the results
- An explicit definition of the product, service or the system and its function

- A definition of the functional unit
    - Functional unit - the unit that is used as reference to which the input and output data are normalized (Menoufi, 2011). It is especially required when two alternatives are compared.
- The details of the system boundaries
    - System boundaries – states the phases in a life span that are to be included in the study (manufacturing, transport, operation, end of use, etc.) There are different types of system boundaries that can be selected from the simplest to the most complex one. Figure 2.4 shows system boundaries defined by ISO 14040.
        - Gate to gate: It is the simplest option that considers the only one value-added process in the entire production chain (Svoboda, 1995). This is usually used in specialized unit process studies which requires specific analysis.
        - Cradle to gate: This is an assessment that includes resource extraction, possible transformations and transportation steps beside production process. In other words, it is conducted from raw material extraction to the factory gate.
        - Cradle to grave: It is one step further from cradle to gate approach by adding the product distribution, use and end of life stages.
        - Gate to grave: It includes the span of after-production to end of life of the product. This is an idea mostly used in market studies of products by assessing the distribution, use and end of life phases separately.
        - Cradle to cradle: This alternative is the most complex one among others. It includes all stages while it also considers recycling option at the end of life disposal step (EdgeEnvironment, 2015).

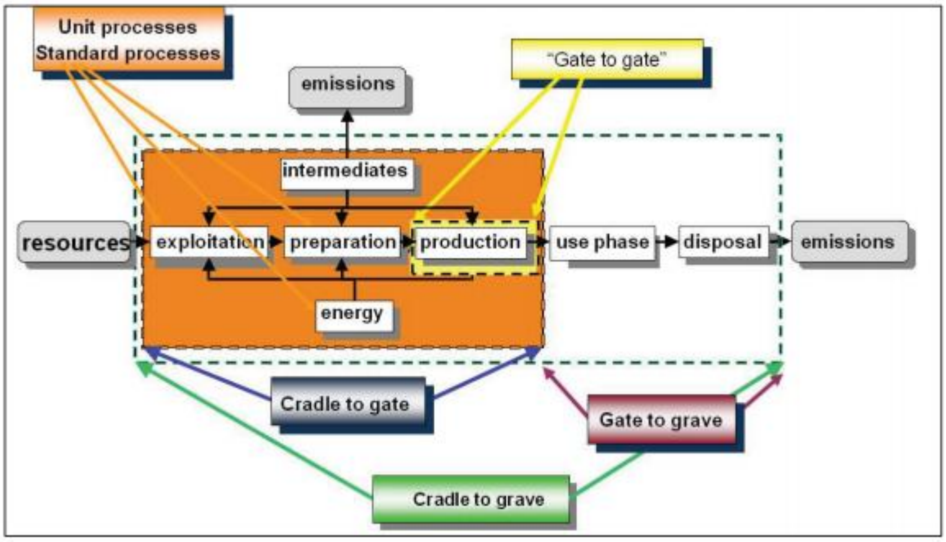

Figure 2.4. System boundaries according to ISO 14044 ("Introduction to Life Cycle Assessment," n.d.)

- Data quality requirements, assumptions and limitations (Goedkoop et al., 2016)
    - It is quite important to determine data quality requirements at the beginning of the study since it affects the results, significantly. This step ensures data acquisition, time and geography reference, technology, precision, completeness and consistency ("Introduction to Life Cycle Assessment," n.d.).
- A critical review, if possible
    - Critical review – process that is conducted for the scientific quality of the analysis. This review proves the consistency of the study to ISO standards and shows the reasonable relations between goal and scope and results.

Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) is the second stage of an LCA which all inputs and outputs are quantified. It also provides information for the improvement opportunities and developing new strategies. The result of this step is a list of material and energy quantities consumed throughout the life cycle of the product, service or system (Stranddorf et al., 2005).

LCI mainly follows following issues:

- Data collection: It is often the most intensive part of an LCA. It is a procedure that should be done to quantify all relevant inputs and outputs including the use of resources and emissions to air, water and land. The results of data collection often tabulated as an inventory list.
- Refining system boundaries: Although the system boundaries are determined in scope definition phase, they can be refined after initial data collection. Due to the iterative nature of LCA, some sub-systems or stages can be eliminated according to the sensitivity analysis. It may also result in the exclusion of material flows which has negligible impact on results.
- Validation of data: Validation of data is done for the improvement of data quality. It should be done in order to check significant anomalies or to determine any missing point in mass or energy balances.
- Relating data to the specific system: Several fundamental data taken from industry or literature may be in arbitrary units. Therefore, they should be conformed to the actual application and be represented in functional units previously determined in scope definition phase.
- Allocation: Sometimes it may not be possible to include all impacts and outputs inside the system boundaries. Therefore, either the system boundaries are expanded or the outputs should be differentiated according to their significance. In case of expansion in system boundaries, there is a disadvantage that the analysis may become too complex. On the other hand, allocation may be a better option although it causes uncertainties due to the difficulty in determining burdens (Menoufi, 2011).

Life Cycle Impact Assessment (LCIA)

ISO 14044:2006 defines Life Cycle Impact Assessment (LCIA) as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system". In other words, the aim of this phase is to interpret the impacts of the use of resource and emission values listed by LCI in terms of the Areas of Protection (AoPs). Areas of Protection is defined as the areas that is to be protected or sustained (Jensen et al., 2002). AoPs are identified in four groups:

- Human health
- Natural environment
- Natural resources
- Man-made environment – in some extent (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010)

According to ISO 14044:2006 standard, LCIA is traditionally classified into several steps:

- Selection of Impact Categories and Classification (mandatory): In the first step, environmental impacts and fundamental flows (resource use and emissions) determined in LCI are referred to the impact categories according to the impacts of each to the different environments (B Corporation, 2008). It is a qualitative and straightforward process that can be created by generating a cause-effect pathway between the environmental intervention and its potential effect.
- Characterization (mandatory): After classification, the impact of each intervention should be quantified by using characterization factors, i.e equivalency factors (B Corporation, 2008). A characterization factor is the quantitative representation of a particular intervention. Quantification is formulated as;

Category Indicator = Σ characterization factor x emission inventory

There are two approaches of characterization affecting the path of the study as midpoint and endpoint approaches. While midpoint model has indicators located somewhere between the life cycle inventory and endpoint categories, endpoint approach models all the way until areas of protection. In other words, endpoint modelling reaches up to the point where environmental effect occurs. Figure 2.5 illustrates the midpoint and endpoint approaches (Menoufi, 2011).

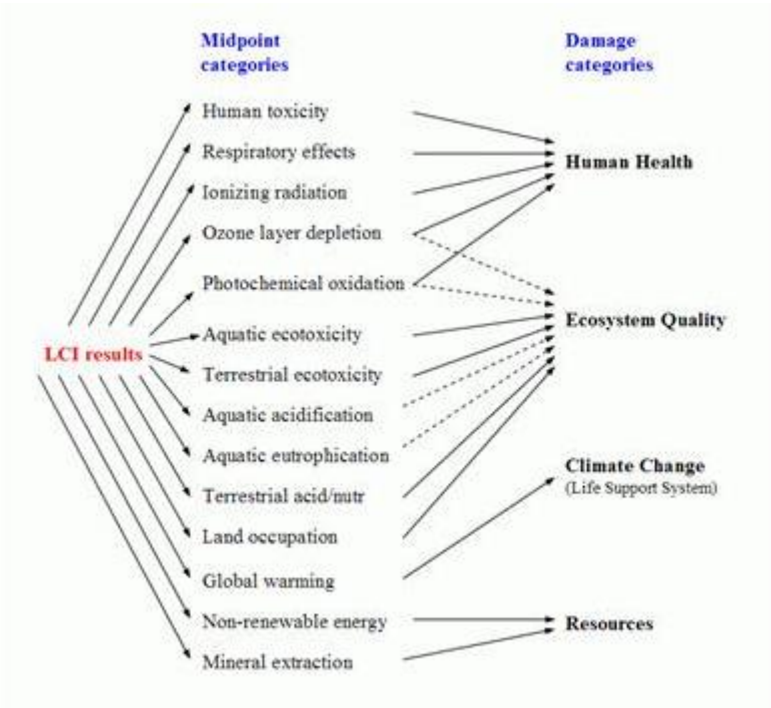

Figure 2.5. Midpoint and endpoint categories (Ruggles et al., 2019)

- Normalization (optional): In order to compare the results coming from different impact categories, the results should be expressed on a common scale. Normalization is done by dividing the results by a reference situation's score. In other words, it provides an opportunity to associate the results with the environmental impact of one person during a full year. While it simplifies the results, it also enables to adding up to results of the different categories due to the fact that they all have the same units. Different LCA methods provide different normalization sets including several regions and years (PRe Consultants, 2014).

- Weighing (optional): It is the process of converting the results the normalized indicators of various impact categories into other values by using weighing factors based on subjective social, political and ethical factors. Basically, it is done by multiplying the weighting factors by the normalized results of each impact category. This is done to estimate the results according to the relative importance of the impact categories (Menoufi, 2011).

Interpretation

Interpretation is the final step of an LCA in which the results are analyzed and conclusions are obtained. In this step, limitations are explained and recommendations are provided according to the results obtained. The main purpose of interpretation step is to provide a clear, transparent and consistent conclusion in accordance with the goal and scope of the study (Khasreen et al., 2009). To do this, several verification checks can be done:

- Completeness check – conducted for the verification of the completeness of the study by checking all environmental issues represent the information from LCI and LCIA
- Sensitivity check – carried on to find whether ultimate results are affected by assumptions, uncertainities or assessment method. It is done by creating a number of "what if" scenarios and changing inputs according to a systematic approach

Consistency check: - done for checking the consistency between project's goal and scope and the results (Menoufi, 2011).

2.3. Integration of LCA to LEED

Although LCA has been used for building industry since 1990s, it is still not as commonly used as in other sectors. Building LCA can be considered as a specific field having its own features and also challenges. Since the product is "the building" in this case, the complexity of the study increases compared to the other products. There are several reasons behind these challenges. First of all, buildings have relatively long life spans, mostly more than 50 years. Therefore, the prediction of the whole life cycle from cradle to grave is quite difficult. Secondly, there are often major renovations or changes done during the life span of the building depending on its form and function. These changes are also unpredictable and may cause very significant impacts on the results. Thirdly, many studies showed that the critical impacts of the buildings are often caused during use phase. Thus, building function and occupant usage behaviors should be well-known to be able to assess the use phase impacts. Lastly, despite the fact that there is very little standardization in building design, each building is unique and therefore requires specific and different choices for an LCA study (Khasreen et al., 2009).

Although there are several constrains mentioned above, the building industry is affected by the trend of sustainable design and environmental-friendly strategies observed in both architectural and construction industries. At this point, LCA gains importance since it enables designers and researchers to compare options and decide which one is a better practice, i.e. to meet project goals. LCA provides a quantitative comparison results for both materials and processes across a wide range of environmental impact performance metrics rather than utilizing imprecise measures commonly used in green building assessment programs up to now (Rodriguez & Simonen, 2017). Table 2.5 summarizes the possible uses of LCA in the construction sector.

Table 2.5. *Possible uses of LCA in construction sector (Zabalzas et al., 2009)*

Type of user	**Stage of the process**	**Aim of using LCA at this stage**
Consultants advising municipalities, urban designers	Preliminary phase	Setting targets at municipality level,defining zones where building is encouraged or prohibited,setting targets for development areas
Property developers or clients	Preliminary phase	Choosing a building site, sizing a project, setting environmental targets
Architects and engineers	Early and detailed design (product development) & Design of a renovation project (product improvement)	Comparing design options

To extend the use of LCA in construction sector, methodologies and initiatives have been more common in the last few years. For example, GRBSs like LEED recently promotes whole building LCAs in its rating system structures. LEED v4 BD+C includes a new credit called Building Life-Cycle Impact Reduction under Material and Resources category. “Whole Building Life Cycle Assessment” is presented as Option 4 under this credit and corresponds to three points with one possible exemplary point. Table 2.6 summarizes LEED credits related to LCA.

Table 2.6. *LCA-related credits in LEED v4 ("LEED v4 LCA credits Made Easy with One Click LCA," n.d.)*

LEED credit	**LEED v4.1 BD+C**	**LEED v4 BD+C**	**LEED v4 BD+C: Homes**	**LEED v4 ID+C**	**LEED v2009 BD+C**
MRc1 Option 4	4+ exemplary + regional priority	3+ exemplary + regional priority	x	x	Mrpc63:1
MRc2 Option 1, Option 2	2	2	1	2	Mrpc52:1 Mrpc61:1
MRc3 Option 1, Option 2	2	2	1	2	Mrpc53:1
Pilot credit: Informing Design Using Triple Bottom Line Analysis	1	1	1	1	1
Pilot credit: Informing Design by Major Credit Category Using Triple Bottom Line Analysis	1	1	x	1	x
Maximum points available	**11 + regional**	**10 + regional**	**3**	**6**	**5**

The main target of this new credit is to provide an early decision of design options in order to reduce environmental impacts. Since LCA eliminates uncertain judgements about water and energy uses or material selections, building professionals can identify more sustainable alternatives and compare them with each other.

A project aiming to achieve points from the "Whole Building Life Cycle Assessment" option must fulfill several requirements:

- The building should improve building life cycle impacts by 10% compared to a baseline building. Performance requirements of baseline building is determined by ASHRAE 90.1-2010 and the LCA study must be conducted by a LCA software.
- The baseline and proposed buildings must be of comparable size, function, orientation and location.
- The energy performance of the proposed building must be at least 5% improved compared to the baseline building for BD+C: New Construction system.
- The life span of both baseline and proposed building must be taken as 60 years including all maintenance and replacement.
- The LCA must be calculated for six listed environmental impact categories (global warming potential (greenhouse gases), in kg CO_2 eq; depletion of the stratospheric ozone layer, in kg CFC-11 eq; acidification of land and water sources, in moles H+ or kg SO_2 eq; eutrophication, in kg nitrogen or kg phosphate; formation of tropospheric ozone, in kg NOx eq, kg O_3 eq, or kg C_2H_4; and depletion of nonrenewable energy resources, in MJ) with three of them, including global warming potential, demonstrating at minimum a 10% reduction.
- Impacts in each category cannot be more than 5% compared to the baseline case.
- The assessment should be conducted as cradle to grave, from design to demolition.

One point from Innovation credit can be earned if there is 10% improvement in each six impact categories (Singh, 2017).

2.3.1. Research Studies

As LCA tool started to be more common in the assessment of the sustainability degree of buildings, studies focusing on this topic eventually increased in the academic field. While some of these studies concentrate on the comparison of buildings having different properties, the others are mostly try to examine various LCA programs according to the results they give. Yet, LCA studies focusing on buildings show a great variation even when the case study buildings are the same due to the methodological choices and assumptions. Consequentially, it creates a doubt through the reliability of LCA when it is used for policy-making in the construction sector. Therefore, there is an urgent need for credible information and benchmark system in LCA in building and construction sector (Säynäjoki et al., 2017).

Emami et al. (2019) conducted a study by comparing two residential buildings consisting of a concrete-element multi-story residential building and a detached wooden house in Finland. LCAs were conducted by both SimaPro and GaBi in order to estimate the uniformities and inconsistencies. All building elements were included in the studies and results were obtained according to ReCiPe Midpoint method. Results were compared in fifteen impact categories. The study showed that selection of LCA tool affects the results, significantly. While the results changed by a percentage of 15% including the biggest difference occurred in Climate Change, the estimates were entirely different in other categories. A solid conclusion was retrieved that there is an urgent work to improve the reliability of the LCA tools in the building sector in order to have a consistent and fair policy-making.

Scheuer et al. (2003) executed an LCA on a 7,300 m^2 six-storey building located in Michigan. The life span of the building was chosen as 75 years and the whole process was conducted according to Environmental Protection Agency (EPA), Society for Environmental Toxicity and Chemistry (SETAC) and International Standard

Organization (ISO) standards. Swiss Agency for the Environment, Forest and Landscape, SimaPro software and Franklin Associates Reports were used as data sources. Impact categories were determined as primary energy consumption, global warming potential, ozone depletion potential, nitrification potential, acidification potential and solid waste generation. For the primary energy consumption, a computer programming was utilized in heating, cooling, ventilation, lighting and water consumption. As a result, HVAC and electricity use were found to be responsible for the 94.4% of the life cycle primary energy consumption. Moreover, it was proven that operation period should be better managed since it has a substantial effect over all life cycle stages.

Kofoworola and Gheewala (2018) completed an LCA of a 38-storey office building in Thailand. According to the scope of the study, the study was conducted as a whole building life cycle assessment including production of materials, construction, operation, maintenance, demolition and disposal in three impact categories as global warming potential, acidification potential and photo-oxidation formation potential. Life span of the building was assumed as 50 years. According to the results, concrete and steel were the two main materials used in the building in terms of both quantity and the environmental impacts in manufacturing phase with the global warming potential percentages of 47% and 24%, respectively. While they accounted for 42% and 37% of acidification potentials, they were responsible for the photo-oxidation formation potential of 30% and 41%, respectively. The results also indicated that electricity use in the operation phase is the most contributing element in a commercial building's life cycle.

There are also studies which are the combination of LCA and GBRS. Humbert et al. (2007) investigated the extent and the burdens of LEED by evaluating important credits included in the rating system. In this scope, LCAs of 45 credits applied to an actual office building in California. The study was conducted by using SimaPro 7 combining with Ecoinvent 1.2. IMPACT 2002+ v2.1 to compare the benefits of different credits among each other. The results were analyzed in 4 impact categories as human health, ecosystem quality, climate change and resource consumption. Moreover, a school and a residential building were also analyzed for a sensitivity analysis. It was seen that operation period of the building, especially electricity consumption, dominates the results. Additionally, waste generation and water consumption have limited but not negligible impacts. Due to the fact that the building is located in California, heating did not have a significant impact on the results. All in all, the credits related to green electricity and waste recycling were found to be more beneficial from environmental point of view. Another striking point of the study was the negative impacts of several credits. In other words, some credits have more burdens than their benefits. Therefore, the study claims that LEED should improve its credit system in order to increase the benefit of all credits in the long-term.

Alshamrani et al. (2014) had a study on three categories of LEED as Energy and Atmosphere, Material and Resources and LCA in order to find the best option for structure and envelope systems for Canadian school buildings. The study comprised of several structural elements such as concrete, steel, masonry and wood and envelope alternatives such as precast panels, steel stud, wood stud and cavity wall. Energy simulation and LCA were conducted by different programs. While energy simulation was executed in eQUEST version 3.64, LCA was performed in ATHENA impact estimator. The results showed that concrete and masonry buildings have higher energy consumption and global warming potential during the stages of manufacturing, construction and demolition. On the other hand, they have less energy consumption and environmental impact during operation stage.

Other relevant studies existing in the literature are listed in Table 2.7.

Table 2.7. *Summary of research studies on LCA and buildings*

Reference	Content	LCA Software	Result
Al Ghamdi et al. (2016)	LCA of a hospital building by using three different LCA programs	Tally, Athena, SimaPro	LCA results showed that the impact of LCA software is dependent on the impact category and the precision in the process of material quantities takeoff.
Sartori and Hestnes. (2006)	Life cycle energy consumption of conventional, low energy and zero energy buildings	-	Low energy buildings are more energy efficient than conventional ones in terms of operational energy use but show high embodied energy results. Yet, reducing operational energy should be the prior target in the design of a building.
Bribina´n et al. (2009)	LCA of a single family home with 222 m2 in Spain	CALENER VYP	The results revealed that embodied energy requires 30% of the primary energy of the building. Secondly, heating was found to be the prior element in the building’ s life-span followed by building materials.
Sinha et al. (2016)	Comparison of the assessment tool of ELP with GaBi and SimaPro by using both a concrete and a wooden building	GaBi, SimaPro ELP	Results showed that calculated energy results are quite close to each other in each assessment tool, but carbon footprint measured in ELP was much lower than the others. This indicates the lower GHG emission intensity per unit energy in Sweden when it is compared to the world and European average.
Kylili et al. (2015)	LCA of a passive house located in Cyprus	EcoHestia	Findings indicated that C20-C25 concrete is the most contributing element in all impact categories except abiotic depletion. Another result obtained from study showed that foundations, floors and wall systems are significant components affecting building’ s environmental performance.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1. Case Study – Prokon Ekon Headquarter Building

Project building, which was constructed as a headquarter building of Prokon Ekon Group Companies, is located on Ankara – Istanbul highway. It serves for the companies dealing with consultancy, engineering, supervision and architectural services. Being in the construction sector for years, the Group wanted to build a sustainable and energy efficient head office building in the empty area they own, near their factory. Therefore, project was registered for the assessment of LEED v2009 for New Construction certification system in October, 2011. An interdisciplinary team including architects, engineers, consultants and managers worked on the energy efficiency and sustainability targets of the project since the beginning of design period. The team conducted comprehensive studies, detailed analyses, regular meetings and site visits in order to manage both design and construction processes until the building obtained its LEED Platinum certification with 89 points in February, 2016.

The building is primarily used as an administrative office located on almost 17,000 m^2 land. The site was previously developed, so a new landscape project consisting of adaptive plants was prepared after the existing storage facilities in the site removed. Figure 3.1 depicts the view of the building after construction.

Figure 3.1. Picture of Prokon Ekon Headquarter Building

General Characteristics: The building has two basement floors, one ground floor and five upper floors with a total gross floor area of 11,728 m^2. General layout plan is described below:

- Second basement floor: includes pump rooms, garages, storage tanks and restrooms
- First basement floor: includes garages, an auditorium, restrooms/changing rooms and equipment rooms
- Ground floor: has a central double height space around which meeting rooms and modular offices are located. This floor also has a cafeteria, information desk and restrooms.
- Offices, meeting rooms and board rooms with circulation corridors are located on remaining floors. Each floor has also restrooms and other amenities.

Main Building Elements: Building consists of two concrete cores enclosed by steel construction. The most significant feature of the building is the steel structure which was design on purpose. Design team wanted to emphasis on steel structure as much as possible for both inside and outside of the building. On the front façade, a console structure (16 m x 22 m x 8 m) having no column support was constructed. In addition, three different material which are glass, aluminum composite panel and ceramic were used on the façades. Figure 3.2 shows general layout and section of the building.

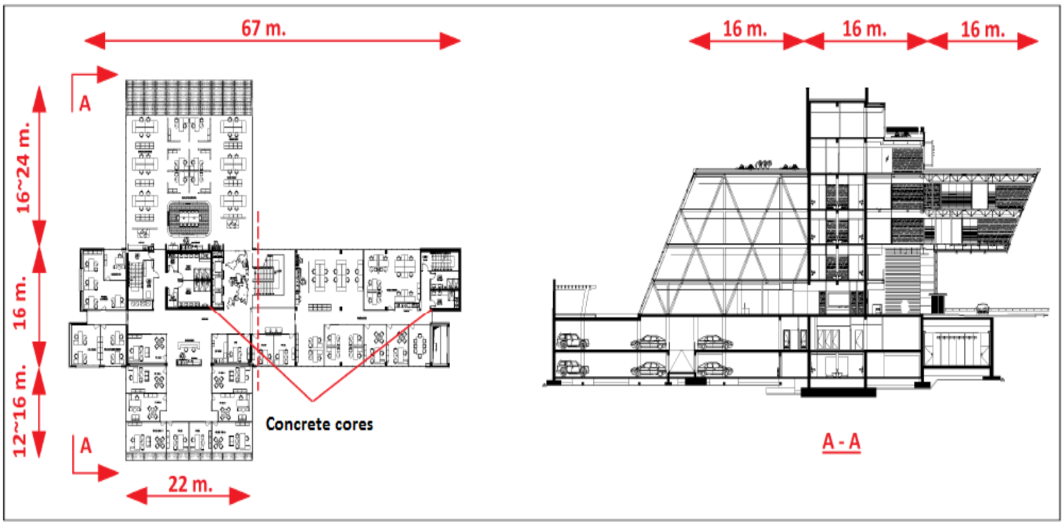

Figure 3.2. Prokon Ekon Headquarter Building General Plan (Prokon Ekon Group, 2017)

Since passive design elements provide a vital performance efficiency for green buildings, design team put an emphasis on the building envelope. To achieve a good thermal performance, insulation and fenestration selections were done studiously. While rock wool and Extruded Polystyrene (XPS) were used for the wall and roof insulation, triple glazed and thermally efficient laminated and tempered glasses were selected for the fenestration. A good protection from heat gain & loss has been achieved with the help of good insulation and also the air gap existing between the glasses. Thus, the capacity of mechanical equipment and operation costs has been decreased.

There are several types of flooring elements in the building such as granite, ceramic, parquet, self-smoothing polyurethane flooring and carpets. All flooring systems were preferred to be certificated according to the standards accepted by LEED. For other building materials such as construction chemicals, low or zero Volatile Organic Compounds (VOC) materials were selected in order to protect indoor environmental quality of the building.

<u>Mechanical Design:</u> After the minimization of heat gain and loss from the building envelope, energy efficient mechanical equipment were selected for meeting the net energy demand of the building.

For heating and cooling, 3 pipe - heat recovery Variable Refrigerant Flow (VRF) system which uses less amount of fossil fuel was installed. This central air conditioning system utilizes water in different temperatures depending on the season. Figure 3.3 shows the working principle of the VRF system in the building:

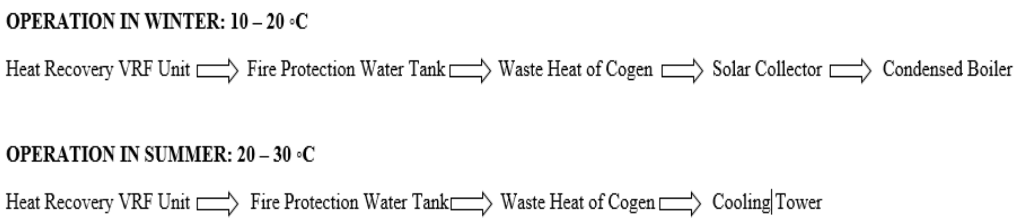

Figure 3.3. Operation principles of VRF system (Prokon Ekon Group, 2017)

Although most of the offices are designed as open offices, each space can be heated or cooled independent from each other. This provides an enhanced comfort for the occupants.

There is also a tri-generation system consisting of an absorption chiller in which waste heat coming from the system is used for cooling purpose during summer while it is utilized for heating in winter time. Besides, the electricity produced feeds base loads like VRF system, fans and pumps. Figure 3.4 clearly shows the working principles of the tri-generation system.

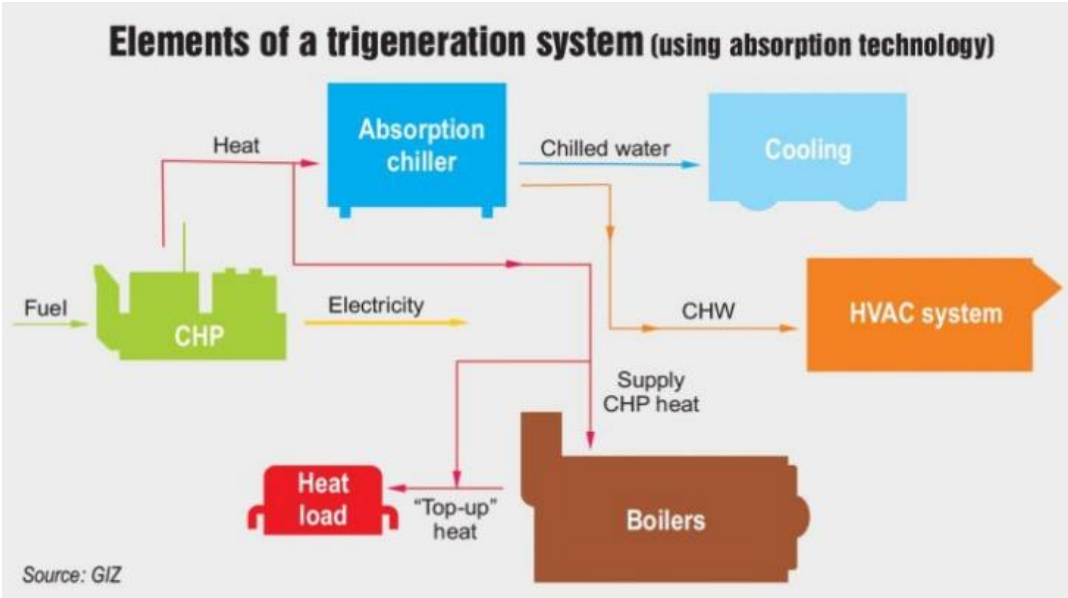

Figure 3.4. Working principles of tri-generation system ("Triple Benefits," 2019)

Ventilation infrastructure was designed as it provides 30% more ventilation compared to ASHRAE 62.1 2007 standard. The system is supported by CO_2 sensors and Variable Air Volume (VAV) devices which enable building operators to adjust outdoor air delivery and fan speeds in order to optimize energy performance. Moreover, air conditioning systems were chosen among the ones with frequency inverters and heat recovery.

On-site renewable energy is provided by photovoltaic panels and solar collectors. While the electricity produced by photovoltaic panels is used for building energy need, solar collectors service for domestic hot water supply. In some seasons, the building is capable of meeting its all electricity demand and even can sell the electricity produced in the building. It is under the category of Energy Plus (A+) due to this reason.

Passive Systems: The building tries to benefit from passive systems as much as possible. There is a solar wall implementation on the south-east façade. This technology provides 5 – 7 °C of pre-heating of fresh air conveyed to the air handling units. It is also beneficial for the thermal storage of the building at night and early morning times in seasonal change periods. In addition to this, solar chimneys are constructed in order to transfer daylight to the zones which are located underground and cannot get enough daylight, such as conference room and garages. There are also sun breakers on the south and south-west façade in order to control the negative impacts of daylight.

Lighting: The building was designed in a way that it gets maximum daylight from outside. Transparency was achieved by using glasses less reflective but allow more light transmittance. Since the steel elements remained visible as a contemporary architecture point of view, the glass façade was selected accordingly in order to make steel elements visible from outside. Lighting fixtures were chosen among high efficiency LED armatures and combined with a lighting automation system including occupancy and daylight sensors.

Building Automation System: All electrical and mechanical systems are monitored and controlled by a building automation system. All consumptions, efficiencies and operation scenarios can be seen and adjusted with the help of this automation system. In this context, if there is a change in any system, it can be seen and fixed easily due to the existing implementations of electronic measurement devices, flowmeters, pressure and temperature sensors, power analyzers, etc.

Water Management: For water management, there are several implementations in order to decrease the use of tap water. Therefore, a rainwater management and greywater system were established in the building. Rainwater is harvested from both building roof and also a portion of hardscape which has a drainage system underground. Collected water is then used for landscape irrigation. On the other hand, greywater is treated by an ultrafiltration system and used for flush fixtures in the building.

In addition, low water, high efficiency water fixtures and pumps with inverters are used in the building.

3.2. LCA Methodology

The study was conducted according to LCA steps described in Section 2.2. The following sections represent the details of LCAs conducted in the scope of the study.

3.2.1. Goal and Scope Definition

In this study, two main goals were determined. The first goal of the study was to compare and analyze the results of two different LCA softwares which are One Click LCA and SimaPro. Detailed information about the programs can be found in Section 3.3.1 and 3.3.2.

Second goal was to assess the environmental impacts of a LEED certified green building and compare them with a conventional building's results. Hereafter the green building will be mentioned as "case study building", which is Prokon Ekon Headquarter Building, while the conventional building will be denoted as "baseline building".

To achieve both goals, four cradle to grave LCAs were conducted within the scope that are shown in Table 3.1.

Table 3.1. *Goal and scope of the study*

Goal	**Building**	**LCA Software**	**System Boundary**	**Remark**
Comparison of two LCA softwares	Case study building	One Click LCA	A1, A2, A3, A4, B4, B5, C3, C4	-
	Case study building	SimaPro	A1, A2, A3, A4, B4, C3, C4	SimaPro (1)
Comparison of the impacts of two different buildings	Baseline building	SimaPro	A1, A2, A3, A4, B1, B4, B6, B7, C2, C3, C4, D	-
	Case study building	SimaPro	A1, A2, A3, A4, B1, B4, B6, B7, C2, C3, C4, D	SimaPro (2)

In LEED v4, MR Credit 1: Building Life Cycle Impact Reduction supports conducting a whole building life cycle assessment so that the project can earn 3 points. Moreover, total possible energy and water point to be earned is 44 over 110. Therefore, it was decided that assessing both water and energy use of the building together with building materials included in LEED's LCA may lead the study to a more comprehensive analysis. Thus, the study consists of fundamental building materials and also energy and water use in the operation phase. Although the main target was also adding water and energy use of the actual building into the calculation in One Click LCA, it was not possible to do it since the purchased version LEED (CML, TRACI and Intl) did not allow to estimate operational water and energy uses. This also made conducting LCA of the conventional building impossible since the major difference between baseline and case study building comes from energy efficient systems. The program also did not allow to take recycling options after demolition into account which posed a limitation in comparison of the results with the estimations conducted in SimaPro. Therefore, in order to be consistent in terms of system boundaries, LCA of the case study building have been performed in SimaPro as two times and denoted as "1" and "2" as presented in Table 3.1.

The main question that was tried to be answered is how the results can change when the same product is used in different LCA programs. Moreover, another essential question to be asked was determined as how much environmental impacts differ from each other when a green and comparable conventional building assessed.

In both programs, the functional unit was determined as 1 m^2 of building area and the lifetime of the building was chosen to be 60 years according to LEED. However, system boundaries were different from each other due to the versions of the programs used, as shown in Table 3.1.

3.2.1.1. Goal and Scope Definition for the Comparison of One Click LCA and SimaPro

There are several types of versions for the building LCA in One Click LCA depending on the scope and the boundary of the analysis. The one used in the study was purchased as compatible with LEED requirements. According to EN standards that are the valid standards for European market for LCA studies, there are several steps defined in a cradle-to-grave LCA which can be selected according to the goal and scope of the study, which is tabulated in Table 3.2.

Table 3.2. *Life cycle stages according to EN 15978 and EN 15804 standards ("Life Cycle Assessment software FAQ," 2018)*

Product Stage			Construction Stage		Use Stage							End-of Life Stage				Benefits Beyond the System Boundary		
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use / application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction / demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	D	D

Considering EN standards, One Click LCA supported several versions having different life cycle stages. According to the scope of the study, LEED CML version was used including life-cycle stages of A1 – A2 – A3 – A4 – B4 – B5 – C3 and C4.

Figure 3.5 represents the system boundary of the study conducted in One Click LCA. The one conducted in SimaPro also has the same system boundary except B5 stage due to lack of data.

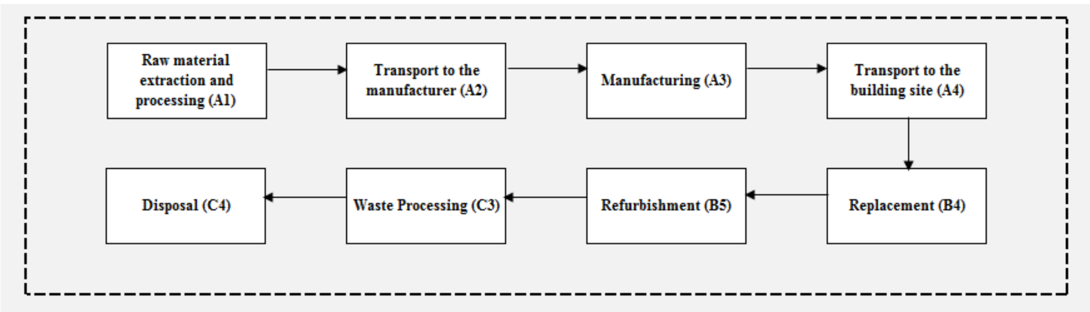

Figure 3.5. System boundary used in One Click LCA

GaBİ and Ecoinvent databases were used for the materials and products. Data used in the study were tried to be chosen among Turkish origin as much as possible. However when it was not available, the ones with European origin were used since most of the materials in One Click LCA were taken from European companies. This may be counted as a limitation for the study.

3.2.1.2. Goal and Scope Definition for the comparison of Baseline and Case Study Building

System boundaries for both baseline and case study building is shown in Figure 3.6:

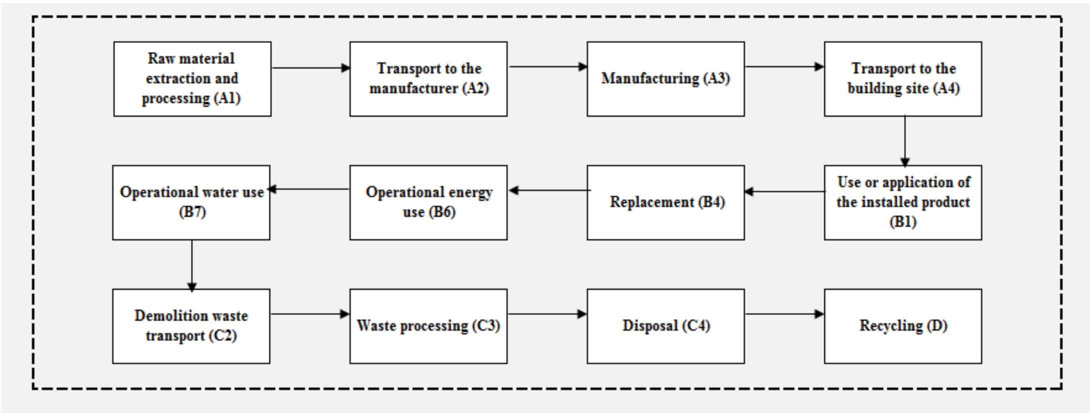

Figure 3.6. System boundary used in SimaPro for the comparison of baseline and case study building

Operational water, energy and natural gas consumptions were also included in the analyses in SimaPro. In both LCAs, Ecoinvent 3 database were tried to be used as much as possible. However, when data was not available, several other ones were used as well. Figure 3.7 shows the databases used in SimaPro:

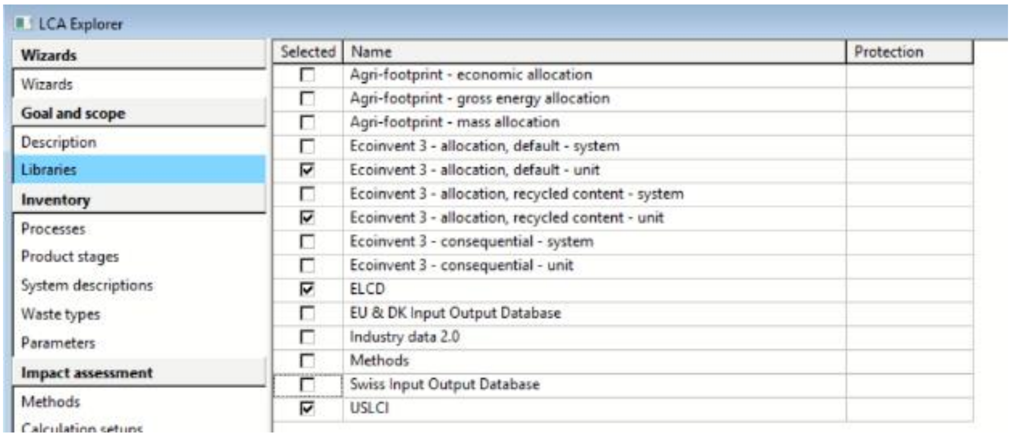

Figure 3.7. A screenshot for the databases used in SimaPro

Unlike old versions of Simapro, SimaPro 8 utilizing Ecoinvent3 does not have a Data Quality Indicator (DQI) Requirements section under Goal and Scope definition part. Instead, the indicators like geography and allocation have been placed in product names. Therefore, selection of each material or product was done according to the DQI requirements of the project. Materials or products were mostly tried to be chosen from local or regional data but due to limitations in availability of local and even regional data, Global scale (GLO) was mostly used.

3.2.2. Data Inventory

Data inventory step was one of the most complicated and time consuming steps during the whole process since construction documents were disordered and there were missing information about some building materials. Therefore, data used in the study was collected from different sources which were basically invoices, construction progress payments, architectural and mechanical projects, building energy simulation report, mechanical equipment lists, manufacturer documents and meters for electricity, water and natural gas. The lifetime of the materials that should be replaced in 60 years was determined by both literature data and also One Click LCA database.

Since it is very important to choose the best alternative option from the database when the exact material or product is not available, following approach was used:

- In such a case, firstly material or product that are technically similar from other local manufacturers was preferred.
- If there was no local manufacturer, other technically similar material or product from generic database was selected.

Building materials and technologies used in the case study building were demonstrated in Table 3.3. It shows the amounts, service lives, distances from the manufacturers and data sources of building materials and mechanical equipment assessed in the study. It is important to note that cabling and piping are neglected. Energy, water and natural gas consumption values for 2018 and were taken from meters installed in the building. Table 3.3 also demonstrates data availability of the materials and systems in both One Click LCA and SimaPro 8.4.1.0. "x" indicates the availability of the material in relevant softwares.

Table 3.3. *Data inventory of Prokon Ekon Headquarter Building*

Material Type	**Quantity**	**Life Time (yr)**	**Distance (km)**	**Data Source***	**One Click LCA**	**Sima Pro**
Building Materials						
Concrete	3,487 m^3	60	22	I	x	x
Steel mesh	18,200 kg	60	40	I	x	x
Reinforcing bar	325,480 kg	60	40	I	x	x
Steel sheet	68,700 kg	60	362	I	x	x

Table 3.3. *Data inventory of Prokon Ekon Headquarter Building (continued)*

Material Type	**Quantity**	**Life Time (yr)**	**Distance (km)**	**Data Source***	**One Click LCA**	**Sima Pro**
Steel sheet	5,800 kg	60	360	I	x	x
Aerated concrete block	3,738 m^2 x 0.1 m	60	120	CPD	x	x
Steel profile	240,750 kg	60	362	I	x	x
Steel profile	232,970 kg	60	360	I	x	x
Aluminum facade	2,926 m^2	40	50	CPD	x	x
Rock wool	5,212 m^2 x 0.08 m	60	40	BESR & CPD	x	x
Gypsum board	5,212 m^2 x 0.0125 m	60	40	BESR & CPD	x	x
Ceramic tile for external	1,605 m^2	60	50	ARP	x	x
Roof membrane	1,535 m^2	35	374	CPD & ARP	x	x
Carpet	1,745 m^2	10	430	I	x	
Granite	1,620 m^2	60	26	ARP	x	x

Table 3.3. *Data inventory of Prokon Ekon Headquarter Building (continued)*

Material Type	**Quantity**	**Life Time (yr)**	**Distance (km)**	**Data Source***	**One Click LCA**	**Sima Pro**
Self-smoothing floor	4,600 m^2	20	60	ARP	x	
Parquet	760 m^2	40	40	I	x	x
Wood beam	1,158 kg	60	40	CPD		x
Windows	2,615 m^2	45	50	BESR	x	x
Coating	267 kg	25	374	I	x	x
Coating	285 kg	25	374	I	x	x
Coating	250 kg	25	374	I	x	x
Coating	285 kg	25	374	I	x	x
Coating	445 kg	10	374	I	x	x
Paint	215 kg	25	374	I	x	x
Coating	245 kg	25	374	I	x	x

Table 3.3. *Data inventory of Prokon Ekon Headquarter Building (continued)*

Material Type	**Quantity**	**Life Time (yr)**	**Distance (km)**	**Data Source***	**One Click LCA**	**Sima Pro**
Cement mortar	8,853 kg	60	37	I	x	x
Mechanical Equipment						
Boiler	1 piece	16	394	MEL	x	x
Solar collector	50 m^2	20	394	MEL	x	x
Photovoltai c panels	3,000 m^2	30	394	MEL	x	x
Circulation pump < 50 W	45 pieces	10	25	MEL	x	x
Circulation pump > 50 W	1 piece	10	25	MEL	x	
Co-generation unit	1 piece	20	394	MEL		x
ABS Chiller	1 piece	25	25	MEL	x	x
Rainwater System						
Concrete	280 m^3	60	22	CPD	x	x
Ultrafiltratio n unit	1 piece	0.5	52	MEL		x

Table 3.3. *Data inventory of Prokon Ekon Headquarter Building (continued)*

Material Type	Quantity	Life Time (yr)	Distance (km)	Data Source*	One Click LCA	Sima Pro
UV Lamp	3 pieces	5	52	MEL		x
Control device	2 pieces	10	52	MEL		x
Greywater System						
Stainless steel	10 m^3	60	28	ARP		x
Ultrafiltration unit	1 pieces	0.5	28	MEL		x
Air compressor	2 pieces	15	28	MEL		x
Potentiometer	2 pieces	10	28	MEL		x
Indoor Water Fixtures						
WC+ Reservoir	90 pieces	20	26	MEL	x	
Faucet	61 pieces	20	26	MEL	x	
Operational Water and Energy Use						
Water	1,954 m^3		Water meter			x

Table 3.3. *Data inventory of Prokon Ekon Headquarter Building (continued)*

Source Type	**Amount for the year 2018**	**Data Source**	**One Click LCA**	**Sima Pro**
Electricity	850,397 kW	Electricity meter		x
Natural gas	46,787 m^3	Natural gas meter		x

*Abbreviations of the data sources are provided as: “I” for invoices, “CPD” construction progress documents, “BESR” for building energy simulation report, “ARP” for architectural projects and “MEL” for mechanical equipment lists.

Since it was very hard to find exactly comparable building with the case study building, baseline building was constructed hypothetically. There are some assumptions used for creating a comparable baseline building:

- All elementary structural building materials were kept as the same with the case study building except aluminum used for the façade and structural steel and iron. While aluminum cladding and structural steel/iron were chosen to be recycled products in actual case, they were selected as first products from raw materials in baseline case.
- Another assumption was done for fenestration. While triple glazing were chosen for the case study building, double glazing windows were preferred in baseline building since conventional buildings mostly have single or double glazing. Due to the lack of data for single glazing in SimaPro, double glazing options were evaluated. In addition to this, aluminum frames were changed into poly vinyl chloride (PVC) by considering the common use of this material in Turkey.

- It was also assumed that there is no on-site renewable energy source utilized by the baseline building. Therefore, solar collectors and photovoltaic panels were eliminated in baseline building.
- There were also slight modifications in mechanical equipment used for heating and cooling. Considering the fact that tri-generation systems are still not common in regular office buildings in Turkey, co-generation unit & ABS chiller were taken out from the calculations. Instead, a fossil fuel boiler was put to the baseline building for heating purpose according to ASHRAE 90.1 2007 standard which was valid for LEED v2009. Table 3.4 and Table 3.5 show the baseline building type and system descriptions according to ASHRAE 90.1 2007. As it can be seen form the Table 3.4 and Table 3.5, baseline building was evaluated under System 7 which requires fossil fuel boiler for heating.

Table 3.4. *Baseline HVAC System Types according to Table G3.1.1A ("Ashrae Standard," 2007)*

BASELINE HVAC SYSTEM TYPES		
Building Type	**Fossil Fuel, Fossil/Electric Hybrid, and Purchased Heat**	**Electric and Other**
Residential	System 1 - PTAC	System 2 - PTHP
Nonresidential and 3 Floors or Less and <2300 m2	System 3 - PSZ-AC	System 4 - PSZ-HP
Nonresidential and 4 or 5 Floors or Less and <2300 m2 or 5 Floors or Less and 2300 m2 to 14,000 m2	System 5 - Packaged VAV with Reheat	System 6 - Packaged VAV with PFB Boxes
Nonresidential and More than 5 Floors or > 14,000m2	System 7 - VAV with Reheat	System 8 - VAV with PFB Boxes

Table 3.*5 Baseline System Descriptions according to Table G3.1.1B ("Ashrae Standard," 2007)*

BASELINE SYSTEM DESCRIPTIONS				
System No.	**System Type**	**Fan Control**	**Cooling Type**	**Heating Type**
1. PTAC	Packaged terminal air conditioner	Constant volume	Direct expansion	Hot-water fossil fuel boiler
2. PTHP	Packaged terminal heat pump	Constant volume	Direct expansion	Electric heat pump
3. PSZ-AC	Packaged rooftop air conditioner	Constant volume	Direct expansion	Fossil fuel furnace
4. PSZ-HP	Packaged rooftop heat pump	Constant volume	Direct expansion	Electric heat pump
5. Packaged VAV with Reheat	Packaged rooftop VAV with reheat	VAV	Direct expansion	Hot-water fossil fuel boiler
6. Packaged VAV with PFP Boxes	Packaged rooftop VAV with reheat	VAV	Direct expansion	Electric resistance
7. VAV with Reheat	Packaged rooftop VAV with reheat	VAV	Chilled water	Hot-water fossil fuel boiler
8. VAV with PFP Boxes	VAV with reheat	VAV	Chilled water	Electric resistance

- It was also assumed that there was no solar passive systems used in the building such as solar wall and daylight tubes utilized by case study building. Although solar wall and daylight tubes were not included in case study building calculations due to the fact that they could not be found in SimaPro database, their positive contribution to heating/cooling load and electricity use were taken into account.
- No rainwater harvesting and grey water system was considered for baseline building.

- Unlike end of life scenario of the case study building, no recycling of recyclable building materials like aluminum and steel assumed after demolition. All demolition waste was assumed to be sent to the landfill.

According to all assumptions done for generating a hypothetical baseline building, data inventory of it is listed in Table 3.6:

Table 3.6. *Data inventory of the baseline building*

Material Type	**Quantity**	**Service Life (yr)**	**Distance (km)**
Building Materials			
Concrete	3,487 m^3	60	22
Steel mesh	18,200 kg	60	40
Reinforcing bar	325,480 kg	60	40
Steel sheet	68,700 kg	60	362
Steel sheet	5,800 kg	60	360
Aerated concrete block	3,738 m^2 x 0.1 m	60	120
Steel profile	240,750 kg	60	362
Steel profile	232,970 kg	60	360
Aluminum facade	2,926 m^2	40	50
Rock wool	5,212 m^2 x 0.08 m	60	40
Gypsum board	5,212 m^2 x 0.0125 m	60	40
Ceramic tile for external walls	1,605 m^2	60	50

Table 3.6. *Data inventory of the baseline building (continued)*

Material Type	**Quantity**	**Service Life (yr)**	**Distance (km)**
Roof membrane	1,535 m^2	35	374
Granite	1,620 m^2	60	26
Parquet	760 m^2	40	40
Wood beam	1,158 kg	60	40
Windows	2,615 m^2	45	50
Coating	267 kg	25	374
Coating	285 kg	25	374
Coating	250 kg	25	374
Coating	285 kg	25	374
Coating	445 kg	10	374
Paint	215 kg	25	374
Coating	245 kg	25	374
Cement mortar	8,853 kg	60	37
Mechanical Equipment			
Boiler	1 piece	16	394
Circulation pump < 50 W	45 pieces	10	25
Operational Water and Energy Use			

Table 3.6. *Data inventory of the baseline building (continued)*

Source Type	Amount for the year 2018	Data Source*
Water	5,592 m^3	WM RSC GSC
Electricity	979,817 kWh	BESR
Natural gas	66,449 m^3	BESR

*Abbreviations of the data sources are provided as: “WM” for water meter, “RSC” for rainwater system calculations, “GSC” for grey water system calculations and “BESR” for building energy simulation report.

It should be noted that although baseline building has the same number of indoor water fixtures, they could not be included in the baseline calculations in SimaPro since SimaPro does not have available data.

Water consumption of the baseline building was calculated by using actual data measured from water meter which is 1,954 m^3 and the combination of the water collected from rainwater and greywater systems. In this scope, total annual water amount collected from rainwater and greywater systems were calculated. As a result, it was seen that 3,360 m^3 rainwater and 278 m^3 greywater were treated and reused on-site. Therefore, water consumption of the baseline building was measured by adding 3638 m^3 reused water to the actual consumption. Additionally, total annual energy and natural gas consumption of the baseline building was taken from the Building Energy Simulation Report prepared for the LEED v2009 EA Prerequisite 2: Minimum Energy Performance. Electricity and natural gas consumptions were found to be 979,817 kWh and 701,038 kWh (66,449 m^3), respectively.

3.2.2.1. Data Selection of the Case Study Building in One Click LCA

According to the available data found in One Click LCA, data selection of the case study building listed in Table 3.7:

Table 3.7. *Data selection of the case study building in One Click LCA*

Input	Resource	Database
Building Materials		
Concrete	Ready mix concrete, excluding rebar, C35/45 (B35 M40), Norway, 2014	Ecoinvent
Steel mesh	Ribbed steel rebar mesh, stainless, 21% zinc, 79% recycled steel, Finland, 2013	GaBi
Reinforcing bar	Carbon steel reinforcing bar (secondary production route – scrap), 98.3% recycled content, Turkey, 2015	GaBi
Steel sheet	Profiled steel sheeting, hot-dip galvanized, Finland, 2014	GaBi
Aerated concrete block	Autoclaved aerated concrete blocks, thicknesses: 5, 7.5, 9, 10, 15, 20, 25, 30, 35, 40 cm, Turkey, 2013	Ecoinvent
Steel profile	Structural steel profiles, generic, 0% recycled content (only virgin materials), I, H, U, L, and T sections, Turkey, 2018	Ecoinvent
Aluminum facade	Aluminum composite panel, curtain walling/facade, mineral filled, 4 mm, 5.85 kg/m2, B2, Turkey, 2016	Ecoinvent
Rock wool	Rock wool insulation, in slabs, L = 0.034 W/mK (034), 0.035 W/mK (035), 40-240 mm, 18-21 kg/m3, Mineral Plus 034 -	GaBi
Gypsum board	Gypsum plaster board, fire resistant, 12.5 mm, 10.6 kg/m2, 848 kg/m3, Turkey, 2015	Ecoinvent

Table 3.7. *Data selection of the case study building in One Click LCA (continued)*

Input	Resource	Database
Ceramic tile for external walls	Ceramic façade cladding, 67.07 kg/m2, 2050 - 2200 kg/m3, Germany, 2016	GaBi
Roof membrane	PVC based, multi-layer, synthetic waterproofing roof sheet, non-woven glass inlay, 1.2 mm, Switzerland, 2015	Ecoinvent
Granite	Granite interior flooring, tiles, 2x40x60 cm, installed with 4 cm adhesive mortar layer, Spain, 2013	GaBi
Parquet	Multi-layer parquet flooring, 14 mm, 9.52 kg/m2, Belgium, 2016	GaBi
Wood beam	Glue laminated wood beam, pine, 540 kg/m3, Spain, 2016	Ecoinvent
Carpet	Tufted carpet tiles, 4.718 kg/m2, France, 2017	Ecoinvent
Windows	Aluminium window system, triple glazed, 1230 x 1480 mm, 72.96 kg, 40.1 kg/m2, Germany, 2017	GaBi
Coating	Acrylic polyurethane coating, 1.5 kg/l, 73% solids/volume, film thickness dry/wet: 60-100/80-140 micrometers, 12-	Ecoinvent
Coating	Two component epoxy coating, 1.6 kg/l, 74% solids/volume, film thickness dry/wet: 60-250/80-340 micrometers,	Ecoinvent
Coating	Waterborne acrylic thin film intumescent coating, 1.4 kg/l, film thickness dry/wet: 210-690/300-1000 micrometers, United	Ecoinvent

Table 3.7. *Data selection of the case study building in One Click LCA (continued)*

Input	Resource	Database
Coating	Acrylic polyurethane coating, 1.5 kg/l, 73% solids/volume, film thickness dry/wet: 60-100/80-140 micrometers, 12-	Ecoinvent
Coating	Waterborne epoxy coating, for carbon steel and galvanized steel, 2.5 kg/l, wet film thickness: 90-160 µm, theoretical	Ecoinvent
Paint	Water based textured paint, latex, 1.28 kg/l, theoretical spreading rate: 5.6 - 1 m2/l, Turkey, 2017	Ecoinvent
Coating	Two component solvent free epoxy coating, 1.496-1.604 kg/l, 98% solids/volume, film thickness dry/wet:	Ecoinvent
Cement mortar	Cement-polymer emulsion mortar, 20-50% cement, 50-80% fillers, 1-10% additives, 1350 kg/m3, high performance	Ecoinvent
Mechanical Equipment		
Boiler	Floor standing gas boiler, French average, P=25kW, France, 2016	Ecoinvent, ELCD
Solar collector	Flat collector, solar installation, Germany, 2015	GaBİ
Photovoltaic panels	Solar panel photovoltaic system, EU average, 2015	Ecoinvent
Circulation pump < 50 W	Circulation pump, < 50 W, Germany, 2015	GaBİ

Table 3.7. *Data selection of the case study building in One Click LCA (continued)*

Input	Resource	Database
Circulation pump > 50 W	Circulator pump, 50 - 250 W, Germany, 2015	GaBİ
ABS Chiller	Water chiller, HVAC, French average, 100 kW, France, 2016	Ecoinvent, ELCD
Rainwater System		
Tank	Stormwater storage tank, France, 2016	Ecoinvent
Indoor Water Fixtures		
WC+ Reservoir	Porcelain WC kit (toilet and tank), France, 2014	Ecoinvent
Faucet	Bathroom mixer faucet, brass, Turkey, 2013	GaBi

Unlike SimaPro, the amount of the materials are entered to the program as a total quantity. The program itself then uses the functional unit and building area for the calculation. Moreover, it provides ease in replacement calculations by automatically estimating the service life of the material and converges it to the calculation results. Waste and disposal scenarios also come by the program content.

For each material, there is a tab for transportation inputs. Practitioner can choose transportation method and enter distances, practically.

3.2.2.2. Data Selection of the Case Study Building in SimaPro (1)

In Ecoinvent 3 which is utilized by SimaPro 8, there are two LCA approaches defined in the UNEP/SETAC Shonan guidance which are "attributional" and "consequential" approaches. In the attributional system modelling, inputs and outputs are attributed to the functional unit of a product system by linking the unit processes of the system according to a normative rule. This approach is mostly used when allocated shares of the activities that contribute to the production, consumption and disposal of the products are investigated. In other words, the main purpose when using this approach is to trace a specific aspect of the product back to its contributing unit processes. Attributional model is mostly used when an environmental impact of a product is investigated. On the other hand, consequential system modelling defines a product system in which the activities are linked in a way that it includes all of them and assesses the expected change as a consequence of a change in demand for the functional unit. This approach answers the questions when the environmental impacts of the full share of the activities are investigated ("Consequential LCA. Why and when?," 2015). Therefore, attributional system modelling approach has been chosen for the study due to the fact that the study aims at quantifying how much environmental footprint the building has. Yet, effect of data selection method was assessed through a sensitivity analysis presented in Section 4.3.3.

In Ecoinvent 3, processes are represented as national, regional or global markets for products. These "market processes" includes inputs for production as well as transportation data. When the specific supplier is not known, using market processes is strongly recommended. On the other hand, "transformation processes" include input data similar to the market processes, but they do not represent transportation data. Therefore, market processes were selected in this study since the initial suppliers of the product materials are not known.

Each data library is structured as two processes which are unit and system processes. Although ultimate results are not affected significantly, there are several important considerations when doing choice between the processes. While a unit process includes only emissions and resource inputs for a specific unit, system process version consists of the inventory result of an overall LCA of a process and often called as "black box". In this study, unit processes were preferred since SimaPro does not allow changes in selected materials if the practitioner wants to change any data embodied in the material section in system processes.

According to all basis explained above, data selection of the case study building is tabulated in Table 3.8:

Table 3.8. *Data selection of the case study building in SimaPro (1)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Building Materials		
Concrete	Concrete, 35 MPa {GLO} market for, Alloc Rec, U	Ecoinvent 3
Steel mesh	Steel rebar, blast furnace and electric arc furnace route, production mix, at plant, GLO S	ELCD
Reinforcing bar	Reinforcing steel {GLO} market for, Alloc Def, U	Ecoinvent 3
Steel sheet	Galvanized steel sheet, at plant/RNA	USLCI
Aerated concrete block	Autoclaved aerated concrete block {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.8. *Data selection of the case study building in SimaPro (1) (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Steel profile	Steel, low-alloyed {GLO} market for, Alloc Def, U	Ecoinvent 3
Aluminum facade	Cladding, crossbar-pole, aluminum {GLO} market for, Alloc Def, U	Ecoinvent 3
Rock wool	Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m^3 RER S	ELCD
Gypsum board	Gypsum plasterboard {GLO} market for, Alloc Rec, U	Ecoinvent 3
Ceramic tile for external walls	Ceramic tine {GLO} market for, Alloc Rec, U	Ecoinvent 3
Roof membrane	Single-ply, white, polyester reinforced PVC roofing membrane, 1.219 mm/m^2/RNA	USLCI
Granite	Natural stone plate, cut {GLO} market for, Alloc Rec, U	Ecoinvent 3
Parquet	Prefinished engineered wood flooring, at engineered wood flooring plant, E/m^3/RNA	USLCI
Wood beam	Glue laminated timber, for indoor use {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.8. *Data selection of the case study building in SimaPro (1) (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Windows	Window frame, aluminum, U=1.6 W/m^{2}K{GLO} market for, Alloc Rec, U	Ecoinvent 3
	Glazing, triple, U<0.5 W/m^{2}K {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Acrylic varnish, without water, in 87.5% solution state {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Acrylic filler {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Paint	Alkyd paint, white, without solvent, in 60% solution state {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Cement mortar	Cement mortar {CH} market for cement mortar, Alloc Rec, U	Ecoinvent 3

Table 3.8. *Data selection of the case study building in SimaPro (1) (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Mechanical Equipment		
Boiler	Gas boiler {GLO} market for, Alloc Rec, U	Ecoinvent 3
Solar collector	Flat plate solar collector, Cu absorber {GLO} market, Alloc Rec, U	Ecoinvent 3
Photovoltaic panels	Photovoltaic cell, multi-Si wafer {GLO} market for, Alloc Rec, U	Ecoinvent 3
Circulation pump < 50 W	Pump, 40 kW {GLO} market for, Alloc Rec, U	Ecoinvent 3
Co-generation unit	Heat and Power co-generation unit, 50 kW electrical, common components for heat+electricity	Ecoinvent 3
ABS Chiller	Absorption chiller, 100 kW {GLO} market for, Alloc Rec, U	Ecoinvent 3
Rainwater System		
Concrete	Concrete, 35 MPa {GLO} market for, Alloc Rec, U	Ecoinvent 3
Ultrafiltration unit	Ultrafiltration module {GLO} market for, Alloc Rec, U	Ecoinvent 3
UV Lamp	Backlight, for liquid crystal display {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.8. *Data selection of the case study building in SimaPro (1) (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Control device	Potentiometer, unspecified {GLO} market for, Alloc Rec, U	Ecoinvent 3
Greywater System		
Stainless steel	Steel, unalloyed {GLO} market for, Alloc Rec, U	Ecoinvent 3
Ultrafiltration unit	Ultrafiltration module {GLO} market for, Alloc Rec, U	Ecoinvent 3
Air compressor	Air compressor, screw-type compressor, 4 kW {GLO} market for, Alloc Rec, U	Ecoinvent 3
Control device	Potentiometer, unspecified {GLO} market for, Alloc Rec, U	Ecoinvent 3
Transportation		
Transport of building materials	Transport, freight, lorry>32 metric ton, Euro6 {GLO} market for, Alloc Rec, U	Ecoinvent 3
Transport of building materials	Transport, freight, lorry>7.5-16 metric ton, Euro6 {GLO} market for, Alloc Rec, U	Ecoinvent 3
Waste Scenario		

Table 3.8. *Data selection of the case study building in SimaPro (1) (continued)*

Outputs to technosphere: Waste and emissions to treatment	**Processes**	**Database**
Demolition waste	Inert waste, for final disposal {CH} market for inert waste, for final disposal, Alloc Rec, U	Ecoinvent 3

As it can be seen from the Table 3.8, some materials were found as m^2 which do not compatible with the software's required units for that specific material. Therefore, they were converted to the mass unit (kg) by using density data found in material specification sheets and then entered to the program. Moreover, there were not a compact rainwater and greywater system in the databases. Therefore, in regard to the study released by Zanni et al. (2018) rainwater and greywater systems were generated as another project in SimaPro and then integrated into the current study since there were not a compact rainwater and greywater system in the databases.

3.2.2.3. Data Selection of the Baseline Building in SimaPro

According to the data selection procedure explained in Sec 3.2.2.2, materials and products chosen for the baseline building are represented in Table 3.9:

Table 3.9. *Data inventory of baseline building in SimaPro*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Building Materials		

Table 3.9. *Data inventory of baseline building in SimaPro (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Concrete	Concrete, 35 MPa {GLO} market for, Alloc Rec, U	Ecoinvent 3
Steel mesh	Steel rebar, blast furnace and electric arc furnace route, production mix, at plant, GLO S	ELCD
Reinforcing bar	Reinforcing steel {GLO} market for, Alloc Rec, U	Ecoinvent 3
Steel sheet	Galvanized steel sheet, at plant/RNA	USLCI
Aerated concrete block	Autoclaved aerated concrete block {GLO} market for, Alloc Rec, U	Ecoinvent 3
Steel profile	Steel, low-alloyed, {GLO} market for, Alloc Rec, U	Ecoinvent 3
Aluminum facade	Cladding, crossbar-pole, aluminum {GLO} market for, Alloc Rec, U	Ecoinvent 3
Rock wool	Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m^3 RER S	ELCD
Gypsum board	Gypsum plasterboard {GLO} market for, Alloc Rec, U	Ecoinvent 3
Ceramic tile for external walls	Ceramic tine {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.9. *Data inventory of baseline building in SimaPro (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Roof membrane	Single-ply, white, polyester reinforced PVC roofing membrane, 1.219 mm/m^2/RNA	USLCI
Granite	Natural stone plate, cut {GLO} market for, Alloc Rec, U	Ecoinvent 3
Parquet	Prefinished engineered wood flooring, at engineered wood flooring plant, E/m^3/RNA	USLCI
Wood beam	Glue laminated timber, for indoor use {GLO} market for, Alloc Rec, U	Ecoinvent 3
Windows	Window frame, poly vinyl chloride, U=1.6 W/m^2K{GLO} market for, Alloc Rec, U	Ecoinvent 3
	Glazing, triple, U<1.1 W/m^2K {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Acrylic varnish, without water, in 87.5% solution state {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Acrylic filler {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.9. *Data inventory of baseline building in SimaPro (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Paint	Alkyd paint, white, without solvent, in 60% solution state {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Cement mortar	Cement mortar {CH} market for cement mortar, Alloc Rec, U	Ecoinvent 3
Mechanical Equipment		
Boiler	Gas boiler {GLO} market for, Alloc Rec, U	Ecoinvent 3
Circulation pump < 50 W	Pump, 40 kW {GLO} market for, Alloc Rec, U	Ecoinvent 3
Water use	Tap water {GLO} market group for, Alloc Rec, U	Ecoinvent 3
Inputs from technosphere: electricity/heat	**Processes**	**Database**
Natural gas	Natural gas, high pressure {GR} import from RU, Alloc Rec, U	Ecoinvent 3

Table 3.9. *Data inventory of baseline building in SimaPro (continued)*

Inputs from technosphere: electricity/heat	**Processes**	**Database**
Electricity	Electricity, low voltage {TR} market for, Alloc Rec, U	Ecoinvent 3
Transport of building materials	Transport, freight, lorry>32 metric ton, Euro6 {GLO} market for, Alloc Rec, U	Ecoinvent 3
Transport of building materials	Transport, freight, lorry>7.5-16 metric ton, Euro6 {GLO} market for, Alloc Rec, U	Ecoinvent 3
Waste Scenario		
Outputs to technosphere: Waste and emissions to treatment	**Processes**	**Database**
Demolition waste	Inert waste, for final disposal {CH} market for inert waste, for final disposal, Alloc Rec, U	Ecoinvent 3

3.2.2.4. Data Selection of the Case Study Building in SimaPro (2)

Data inventories of the both LCAs (1 & 2) belonging to the case study building are quite similar except inclusion of operational water and energy use and disposal scenarios. Accordingly, data selection of the LCA of the case study building conducted for the comparison with baseline building was shown in Table 3.10.

Table 3.10. *Data selection of the case study building in SimaPro (2)*

Inputs from technosphere: materials/fuels	Processes	Database
Building Materials		
Concrete	Concrete, 35 MPa {GLO} market for, Alloc Rec, U	Ecoinvent 3
Steel mesh	Steel rebar, blast furnace and electric arc furnace route, production mix, at plant, GLO S	ELCD
Reinforcing bar	Reinforcing steel {GLO} market for, Alloc Def, U	Ecoinvent 3
Steel sheet	Galvanized steel sheet, at plant/RNA	USLCI
Aerated concrete block	Autoclaved aerated concrete block {GLO} market for, Alloc Rec, U	Ecoinvent 3
Steel profile	Steel, low-alloyed {GLO} market for, Alloc Def, U	Ecoinvent 3
Aluminum facade	Cladding, crossbar-pole, aluminum {GLO} market for, Alloc Def, U	Ecoinvent 3
Rock wool	Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m^3 RER S	ELCD
Gypsum board	Gypsum plasterboard {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.10. *Data selection of the case study building in SimaPro (2) (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Ceramic tile for external walls	Ceramic tine {GLO} market for, Alloc Rec, U	Ecoinvent 3
Roof membrane	Single-ply, white, polyester reinforced PVC roofing membrane, 1.219 mm/m^2/RNA	USLCI
Granite	Natural stone plate, cut {GLO} market for, Alloc Rec, U	Ecoinvent 3
Parquet	Prefinished engineered wood flooring, at engineered wood flooring plant, E/m^3/RNA	USLCI
Wood beam	Glue laminated timber, for indoor use {GLO} market for, Alloc Rec, U	Ecoinvent 3
Windows	Window frame, aluminum, U=1.6 W/m^{2}K{GLO} market for, Alloc Rec, U	Ecoinvent 3
	Glazing, triple, U<0.5 W/m^{2}K {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Acrylic varnish, without water, in 87.5% solution state {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Acrylic filler {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.10. *Data selection of the case study building in SimaPro (2) (continued)*

Inputs from technosphere: materials/fuels	Processes	Database
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Paint	Alkyd paint, white, without solvent, in 60% solution state {GLO} market for, Alloc Rec, U	Ecoinvent 3
Coating	Coating powder {GLO} market for, Alloc Rec, U	Ecoinvent 3
Cement mortar	Cement mortar {CH} market for cement mortar, Alloc Rec, U	Ecoinvent 3
Mechanical Equipment		
Boiler	Gas boiler {GLO} market for, Alloc Rec, U	Ecoinvent 3
Solar collector	Flat plate solar collector, Cu absorber {GLO} market, Alloc Rec, U	Ecoinvent 3
Photovoltaic panels	Photovoltaic cell, multi-Si wafer {GLO} market for, Alloc Rec, U	Ecoinvent 3
Circulation pump < 50 W	Pump, 40 kW {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.10. *Data selection of the case study building in SimaPro (2) (continued)*

Inputs from technosphere: materials/fuels	Processes	Database
Co-generation unit	Heat and Power co-generation unit, 50 kW electrical, common components for heat+electricity	Ecoinvent 3
ABS Chiller	Absorption chiller, 100 kW {GLO} market for, Alloc Rec, U	Ecoinvent 3
Rainwater System		
Concrete	Concrete, 35 MPa {GLO} market for, Alloc Rec, U	Ecoinvent 3
Ultrafiltration unit	Ultrafiltration module {GLO} market for, Alloc Rec, U	Ecoinvent 3
UV Lamp	Backlight, for liquid crystal display {GLO} market for, Alloc Rec, U	Ecoinvent 3
Control device	Potentiometer, unspecified {GLO} market for, Alloc Rec, U	Ecoinvent 3
Greywater System		
Stainless steel	Steel, unalloyed {GLO} market for, Alloc Rec, U	Ecoinvent 3
Ultrafiltration unit	Ultrafiltration module {GLO} market for, Alloc Rec, U	Ecoinvent 3
Air compressor	Air compressor, screw-type compressor, 4 kW {GLO} market for, Alloc Rec, U	Ecoinvent 3

Table 3.10. *Data selection of the case study building in SimaPro (2) (continued)*

Inputs from technosphere: materials/fuels	**Processes**	**Database**
Control device	Potentiometer, unspecified {GLO} market for, Alloc Rec, U	Ecoinvent 3
Water use	Tap water {RER} market group for, Alloc Rec, U	Ecoinvent 3
Input from technosphere: electricity/heat	**Processes**	**Database**
Natural gas	Natural gas, high pressure {GR} import from RU, Alloc Rec, U	Ecoinvent 3
Electricity	Building can meet its own energy demand from the photovoltaic panels installed.	-
Transport of building materials	Transport, freight, lorry>32 metric ton, Euro6 {GLO} market for, Alloc Rec, U	Ecoinvent 3
Transport of building materials	Transport, freight, lorry>7.5-16 metric ton, Euro6 {GLO} market for, Alloc Rec, U	Ecoinvent 3
Waste Scenario		
Outputs to technosphere: Waste and emissions to treatment	**Processes**	**Database**
Aluminum	Aluminum (waste treatment) {GLO} recycling of aluminum, Alloc Def, U	Ecoinvent 3

Table 3.10. *Data selection of the case study building in SimaPro (2) (continued)*

Outputs to technosphere: Waste and	**Processes**	**Database**
Steel	Steel and iron (waste treatment) {GLO} recycling of steel and iron, Alloc Def, U	Ecoinvent 3
Other wastes	Inert waste, for final disposal {CH} market for inert waste, for final disposal, Alloc Rec, U	Ecoinvent 3

3.2.3. Impact Assessment

There are a number of impact assessment methods available for whole building life cycle assessments. However, LEED especially prefers TRACI 2.1, CML 2002 and ReCiPe characterization methods for the assessment (Rodriguez & Simonen, 2017). Moreover, as being developed specifically for green building certification programs, One Click LCA only uses CML method for the European market while it utilizes TRACI for North American projects. Therefore, CML method was chosen in both softwares as the impact assessment methodology.

CML methodology was developed by Institute of Environmental Science at the University of Leiden. It is a commonly used and considerably comprehensive methodology mostly used in Europe and comprises midpoint categories. It can only execute characterization and normalization steps and cannot give damage assessment, weighing and single score results.

The impact categories selected for the study were also determined according to LEED requirements. In both One Click LCA and SimaPro, the study includes climate change, acidification, eutrophication, ozone layer depletion, photochemical oxidation and depletion of abiotic resources although CML - baseline version has several more impact categories. Table 3.11 shows the characterization factors used in CML method.

Table 3.11. *Characterization factors used in CML method (Life Cycle Association of New Zealand, 2017)*

Impact Category	Indicators	Area of Protection
Global Warming (GWP100)	(kg CO_2 eq)	Human and ecosystem health
Acidification Potential (AP)	(kg SO_2 eq)	Ecosystem health
Impact Category	**Indicators**	**Area of Protection**
Eutrophication Potential (EP)	(kg PO_4 eq)	Ecosystem health
Stratospheric Ozone Depletion Potential (ODP)	(kg CFC-11 eq)	Human and ecosystem health
Photochemical Ozone Formation Potential (POFP)	(kg C_2H_4 eq)	Human and ecosystem health
Abiotic Depletion Potential – Fossil fuel (ADP - Fossil fuel)	(MJ, net calorific value)	Natural resources

One Click LCA does not execute a normalization step. Therefore, only characterization results were used while comparing the results of actual building by both One Click LCA and SimaPro. However, normalization was used for the comparison of baseline and case study building results' which were both conducted by SimaPro.

SimaPro has several normalization methods. Each of them covers different regions and years.

- World 1990, 1995, 2000
- EU25 and EU25+3, 2000
- West Europe, 1995
- Netherlands, 1997 (PRe Consultants, 2014)

Among all of these, World 2000 was chosen as the normalization factor since most of the materials were selected from global scale (GLO). Accordingly, normalization factors used in the study are listed as;

- 4.18E+13 kg CO_2 eq/ yr for GWP,
- 2.30E+8 kg CFC eq/yr for ODP
- 2.39E+11 kg SO_2 eq/yr for AP,
- 1.58E+11 kg PO_4 eq/yr for EP,
- 4.01E+10 kg C_2H_2 eq for/yr POFP (Shen and Patel, 2010).

SimaPro 8.4.1.0 was used for both comparison analyses in the study.

3.2.4. Interpretation

In the last step, the impacts of building materials and systems were evaluated in the six impact categories. While only characterization results were evaluated in the comparison of One Click LCAand SimaPro results, normalization was also used to compare the baseline and actual building results.

3.3. LCA Softwares Used

In this study, two different LCA softwares were used. First one is SimaPro which is one of the widely used LCA program all over the world. The other one is One Click LCA that was developed for especially LCA of buildings.

3.3.1. One Click LCA

One Click LCA is a software released by Bionova Ltd. The software was developed in order to calculate environmental footprints of construction projects and products and mostly used by architects, structural engineers, environmental consultants, CSR specialists, green building professionals and quantity surveyors. In addition to LCA, the software also provide solutions for greener material tracking, site tracking, climate resiliency, use phase emissions, EN15804-compliant Environmental Product Declarations (EPDs) and infrastructure construction assessments.

The most significant reason in selecting this tool for this study is that the program is specialized for building LCA and supports GBRS such as LEED and BREEAM. For an LCA study, data requirements of different GRBS can change significantly. While some of them requires methodological consistency and data verification by a third party, some of them prefers more practical ways to conduct an LCA. LEED v4 encourages the use of simplified LCA tools by providing aggregate data which makes LCA less time-consuming and costly. However, this may sometimes lead the study to be less accurate compared to the other tools' results. This may be considered as a disadvantage (Bendewald & Zhai, 2013).

The main advantage of the software is its quickness and user-friendly interface since normally LCA takes much time and effort during the process. The report delivered at the end of the assessment can also be used to get credits for LEED and BREEAM. Moreover, it can also calculate the life-cycle costs of the projects ("One Click LCA allows everyone to do environmental assessments for buildings and products," 2018).

The platform has been third party certified for compliancy with ISO and EN standards which are basically;

- EN 15978
- ISO 14040 & ISO 14044
- ISO 21931-1
- ISO 21929-1
- EN 15804

Another advantage of the software is the industry-leading data integration abilities. It can support several integrations such as IFC (Industry Foundation Classes, the international standard – ISO 16739- for BIM), Autodesk Revit versions 2016, 2017, 2018 and 2019, ArchiCAD - 18 and higher, DesignBuilder 5.1 and upwards and Excel and CSV formats. This abilities enable users to upload and access quick information via software (“Life Cycle Assessment from BIM, Excel, gbXML, and more,” n.d.)

One Click LCA reviews, verifies and integrates data from different public and private sources. All data collected is reviewed by Building Research Establishment for verification. Data coverages include European, North American, Asia Pacific, Middle Eastern and South American databases. The information are based on manufacturer or product category EPDs collected from 26 different EPD databases in addition to data taken from building material manufacturers. Besides, software benefits from Oekobau.dat and IMPACT resulting in more than 10.000 different building material resources in total. If there is no proper database for a specific country, the tool allows the user to localize the data to get more accurate results. Additionally, there is an algorithm that provides proper selection options to the user according to the data quality requirements of the project (“Local data means better results,” 2018). The software conducts assessments both via CML and Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) methods. While CML is required by EN15978 and EN15804 standards for European markets, TRACI is used for North American markets. The results are displayed as graphs, tables and reports separated and demonstrated according to the emission categories (“Life Cycle Assessment software FAQ,” 2018).

3.3.2. SimaPro

SimaPro, which was developed by PRe Sustainability, is a world leading LCA software package that has implementation in more than 80 countries. It is a tool for collecting, analyzing and monitoring sustainability data of product and services. Additionally, it is considered as a useful tool for many applications such as carbon footprint calculation, product design and eco-design, Environmental Product Declarations, environmental impact of products and services, environmental reporting (GRI), determining of Key Performance Indicators (KPI), etc. (“SimaPro LCA Software,” n.d.).

SimaPro is supported by many LCI databases including Ecoinvent, Agri-footprint, ELCD, Swiss Input Output Database and USLCI providing a large amount of data. It also has many impact assessment methods commonly used in this field. With the help of the multi-user version, teams can work simultaneously from different locations. It can be used for many different fields of engineering. However, it requires quite more time investment to learn and excel the software (Han & Srebric, n.d.).

Conducting a building life cycle assessment in SimaPro is a tedious work since many details should be identified during the process. However, although it can be considered as a complex LCA tool among all others that provide general analyses, it has the flexibility needed for the complicated building models due to its powerful calculation engine (Han & Srebric, n.d.).

CHAPTER 4

RESULTS AND DISCUSSION

4.1. One Click LCA Results

4.1.1. LCA of Case Study Building by Using One Click LCA

Due to the structural properties of One Click LCA, the results are only given on characterization basis. It also gives characterization results as whole building results and the values for per m^2. One significant feature in displaying results is that One Click LCA provides results according to the life cycle stages of the LCA. In other words, the program demonstrates summary of the results in each impact category by cumulating life cycle stages rather than showing characterization results of each material or product.

Table 4.1 represents total characterization results of the case study building. Detailed characterization results including per product/material is given in Appendix A.

Table 4.1. *One Click LCA total characterization results*

		Impact Category**					
LCA Stage*	**Process**	**GWP** (kg CO_2 eq)	**ODP** (kg CFC11 eq)	**AP** (kg SO_2 eq)	**EP** (kg PO_4 eq)	**POCP** (kg C_2H_4 eq)	**ADP-F** (MJ)
A1 A2 A3	Construction Materials	5.30E6	3.00E-1	2.29E4	4.97E3	3.39E3	7.51E7
A4	Transport to site	3.55E4	6.06E-3	8.50E1	1.82E1	3.39E0	6.49E5

Table 4.2. *One Click LCA total characterization results (continued)*

B4 **B5**	Maintenance and material replacement	1.34E6	1.50E-1	5.64E3	3.17E3	6.19E2	1.95E7
C3 **C4**	Deconstruction	3.69E4	9.83E-4	2.05E2	5.16E1	2.59E1	6.36E5
For whole building		**6.71E6**	**4.56E-1**	**2.88E4**	**8.21E3**	**4.04E3**	**9.59E7**
For per m^2		**5.72E2**	**3.89E-5**	**2.46E0**	**7.00E-1**	**3.44E-1**	**8.18E3**

*Please see Table 3.2 for the definitions of the abbreviations for the LCA stages.

**Please see Table 3.11 for the definitions of the abbreviations for the impact categories.

According to the whole building life cycle assessment CML method, One Click LCA gives the net distribution of the results for 60-year time span as in Table 4.2. It can be clearly seen from Table 4.1 that life cycle stage A1-A3 (Materials) has the most outstanding effect on building's life cycle in all impact categories. The stage B1-B5 (Maintenance and Replacement) has also considerable effect when it is compared to the other two stages as A4 (Transportation) and C1-C4 (Deconstruction).

Table 4.3. *Percentage distribution by life cycle stages in One Click LCA*

Impact category	**A1 – A3 Materials (%)**	**A4 Transportation (%)**	**B1 – B5 Maintenance and Replacement (%)**	**C1 – C4 End of life (%)**
GWP	78.8	0.5	20.0	0.5
ODP	65.6	1.3	32.8	0.2
AP	79.4	0.2	19.5	0.7
EP	60.5	0.2	38.5	0.6
POFP	83.9	0.08	15.3	0.6
ADP – Fossil fuel	78.2	0.6	20.3	0.6

Characterization of each impact category is also graphically shown in Figure 4.1 – 4.6. In fact, those graphs are not given by One Click LCA but rather were prepared by data taken from detailed report that the program gives. Accordingly, structural steel (2.24E+02 kg CO_2 eq), photovoltaic panels (9.25E+01 kg CO_2 eq), aluminum window system (6.16E+01 kg CO_2 eq), concrete (5.74E+01 kg CO_2 eq), aluminum composite panel (3.62E+01 kg CO_2 eq), reinforcing steel (2.48E+01 kg CO_2 eq), galvanized steel sheet (1.76E+01 kg CO_2 eq) and ceramic façade cladding (1.26E+01 kg CO_2 eq) were found to be important components on GWP. Total GWP was found as 5.72E+02 kg CO_2 eq. Figure 4.1 shows GWP characterization results of the case study building in One Click LCA.

Figure 4.2 shows ODP characterization results of the case study building in One Click LCA. As it can be seen from Figure 4.2, photovoltaic panel system (2.18E-05 kg CFC-11 eq) dominated ODP results. It was followed by structural steel (1.09E-05 kg CFC-11 eq), concrete (1.69E-06 kg CFC-11 eq), aluminum window system (1.38E-06 kg CFC-11 eq) and aluminum composite panel (1.11E-06 kg CFC-11 eq). Total ODP was determined as 3.89E-05 kg CFC-11 eq.

Figure 4.3 shows AP characterization results of the case study building in One Click LCA. AP characterization results showed that structural steel (1.19E+00 kg SO_2 eq) has the most significant effect in building's life cycle. Photovoltaic panels (5.45E-01 kg SO_2 eq), aluminum window system (2.12E-01 kg SO eq) and reinforcing steel (1.16E-01 kg SO_2 eq) come after structural steel as other significant building elements. Total AP was measured as 2.46E+00 kg SO_2 eq.

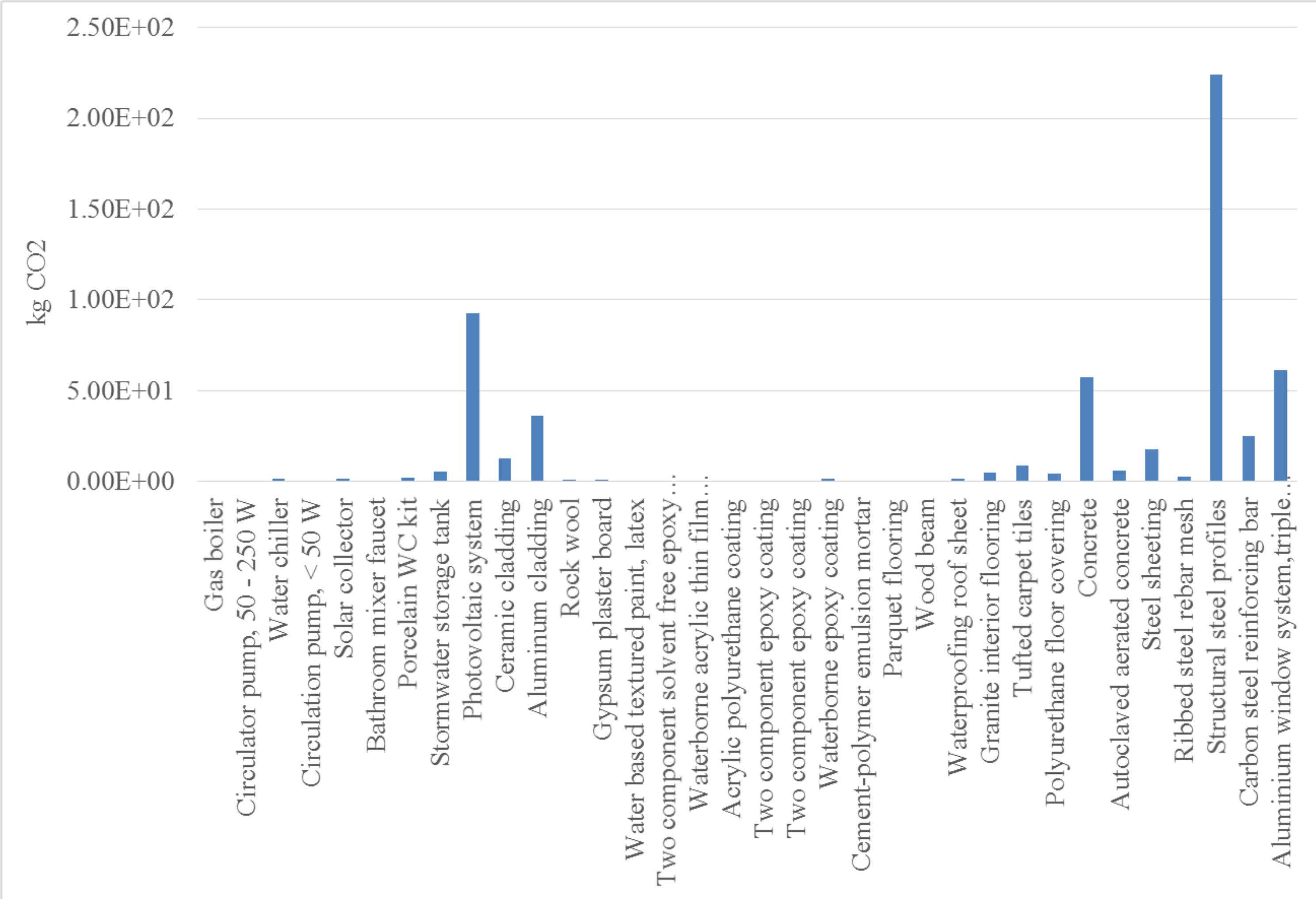

Figure 4.1. GWP characterization results of the case study building in One Click LCA

Figure 4.2. ODP characterization results of the case study building in One Click LCA

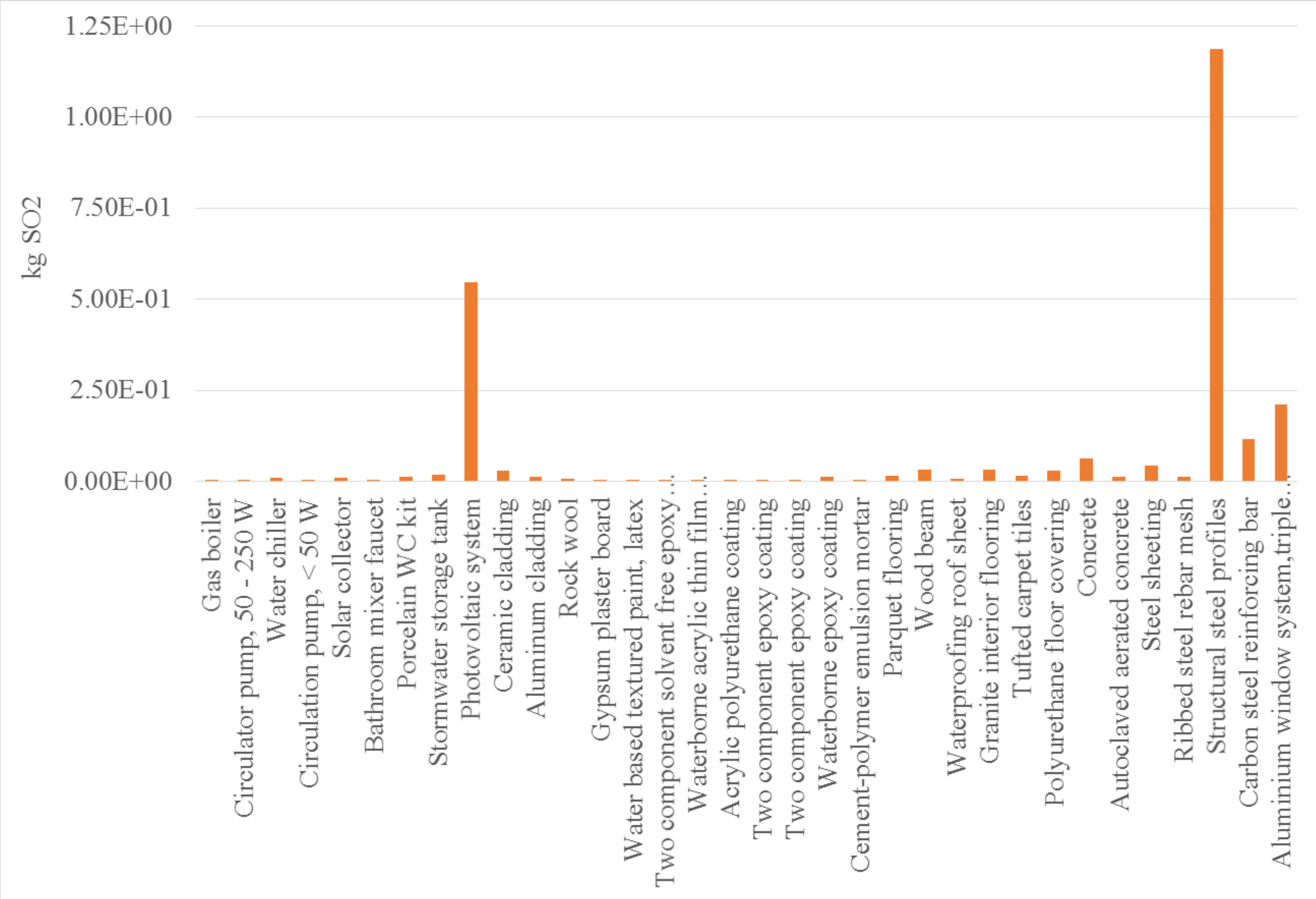

Figure 4.3. AP characterization results of the case study building in One Click LCA

Figure 4.4 shows EP characterization results of the case study building in One Click LCA. Ranking for most contributing elements for EP was found as photovoltaic panels (2.68E-01 kg PO_4 eq), aluminum composite panel (2.13E-01 kg PO_4 eq), structural steel (1.15E-01 kg PO_4 eq), aluminum window system (2.68E-02 kg PO_4 eq), reinforcing steel (1.11 E-02 kg PO_4 eq) and concrete (1.05 kg PO_4 eq). Total EP was calculated as 7.01E-01 kg PO_4 eq.

Figure 4.5 shows POFP characterization results of the case study building in One Click LCA. Total POFP was measured as 3.45E-01 kg C_2H_4 eq. The biggest share belongs to concrete with a characterization value of 1.43E-01 kg C_2H_4 eq. Structural steel (7.89E-02 kg C_2H_4 eq) was found to be the second highest component followed by aluminum composite panel (4.93E-02 kg C_2H_4 eq). Other important building elements were listed as aluminum window system (2.19E-02 kg C_2H_4 eq), and photovoltaic panels (1.08E-02 kg C_2H_4 eq).

Figure 4.6 shows ADP-Fossil fuel characterization results of the case study building in One Click LCA. In ADP-Fossil fuel results, structural steel (3.21E+03 MJ), photovoltaic panels (1.39E+03 MJ), aluminum window system (8.47E+02 MJ), granite flooring (6.64E+02 MJ), aluminum composite panel (3.97E+02 MJ), concrete (3.76E+02 MJ), reinforcing steel (3.15E+02 MJ), ceramic façade cladding (1.90E+02 MJ), steel sheets (1.35 E+02 MJ), tufted carpet tiles (1.29E+02 MJ), polyurethane floor covering (1.22E+02 MJ) and stormwater storage tank (1.08E+02 MJ) showed the highest impact. Total ADP-Fossil fuel was determined as 8.18E+03 MJ.

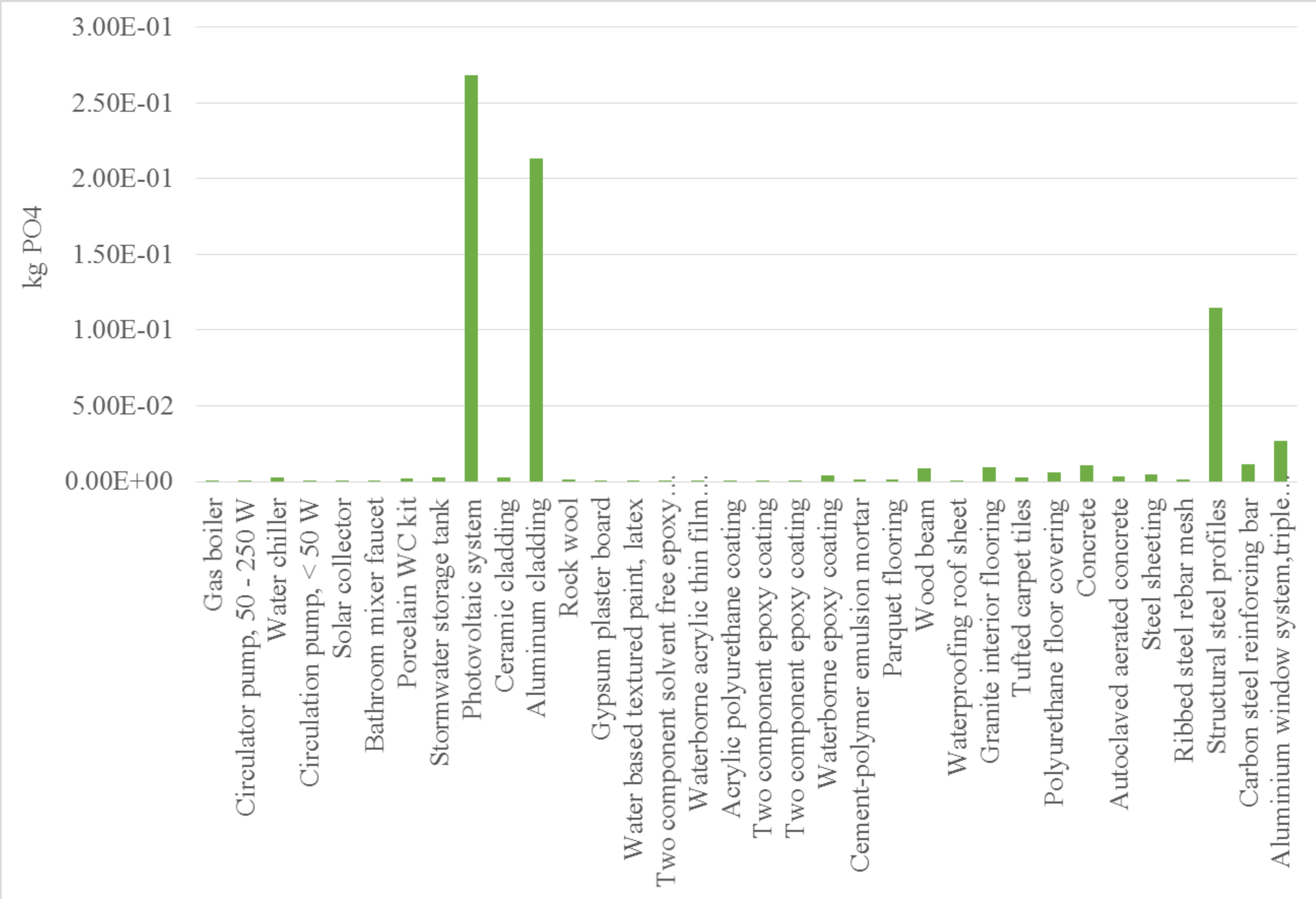

Figure 4.4. EP characterization results of the case study building in One Click LCA

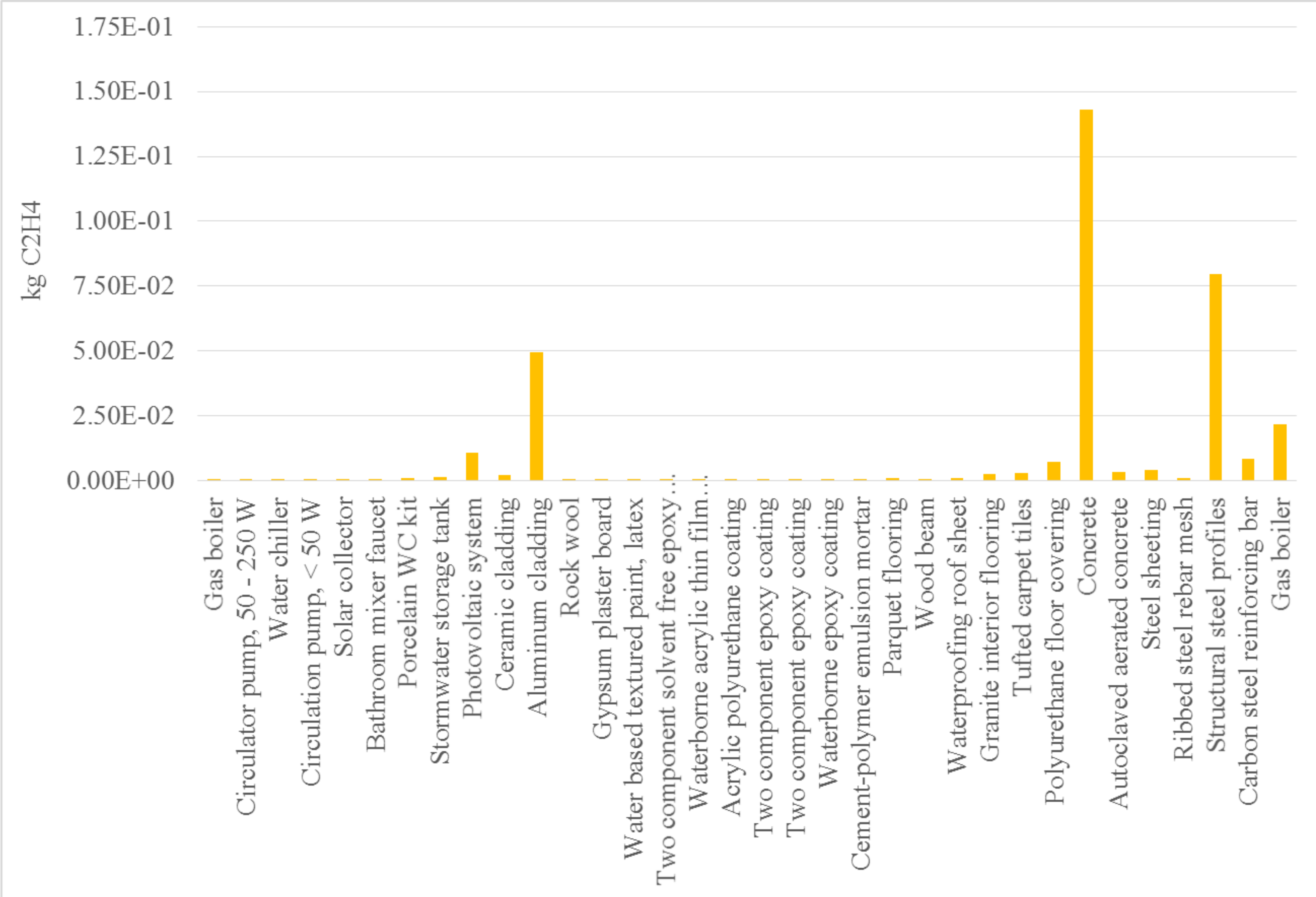

Figure 4.5. POFP characterization results of the case study building in One Click LCA

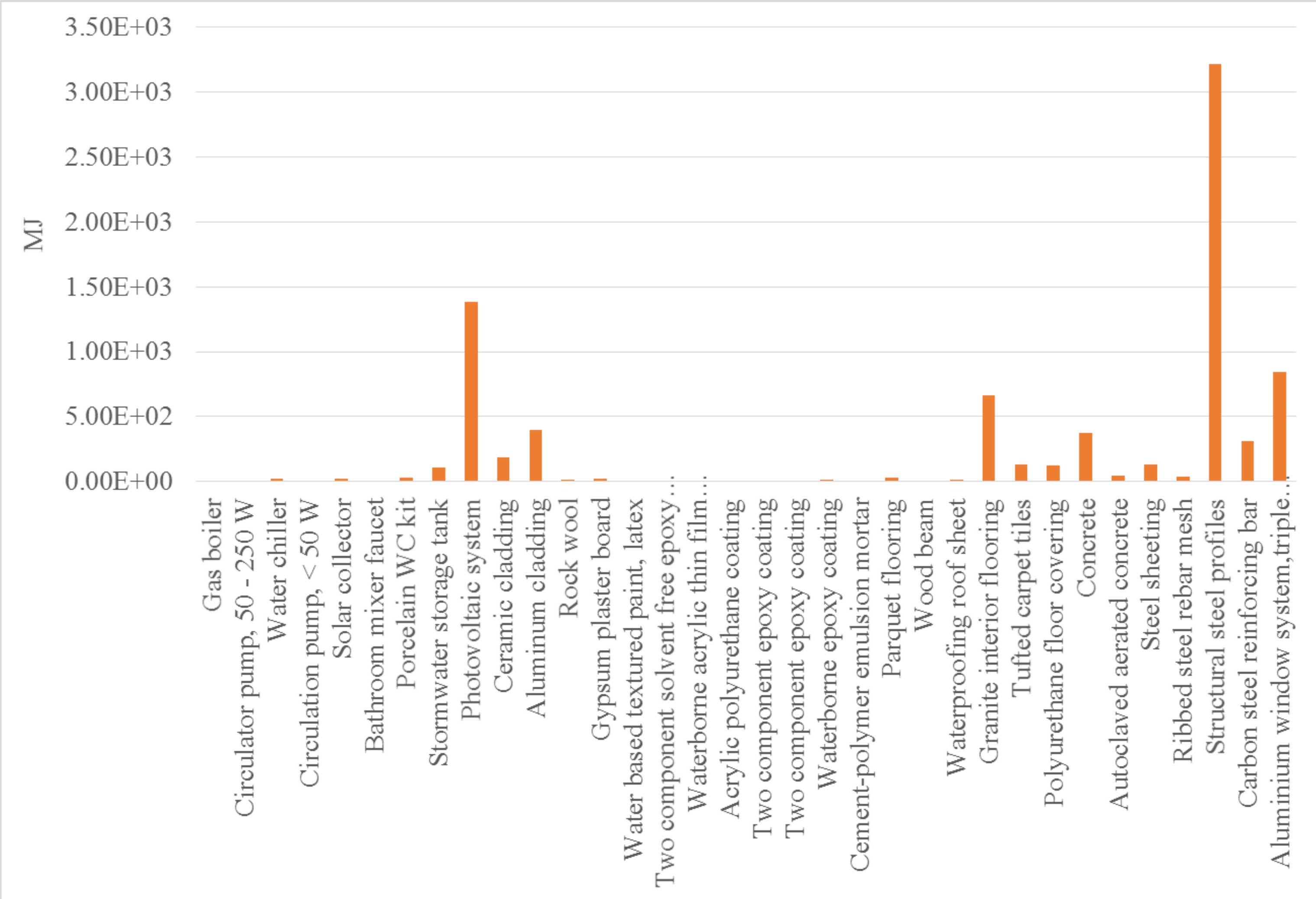

Figure 4.6. ADP-Fossil fuel characterization results of the case study building in One Click LCA

Figure 4.7 summarizes the total characterization results of the case study building obtained from One Click LCA. In order to compare the level of impacts caused by each impact category, the results have to be normalized. However, since One Click LCA does not yield normalization, a graph indicating normalized values could not be provided in this case.

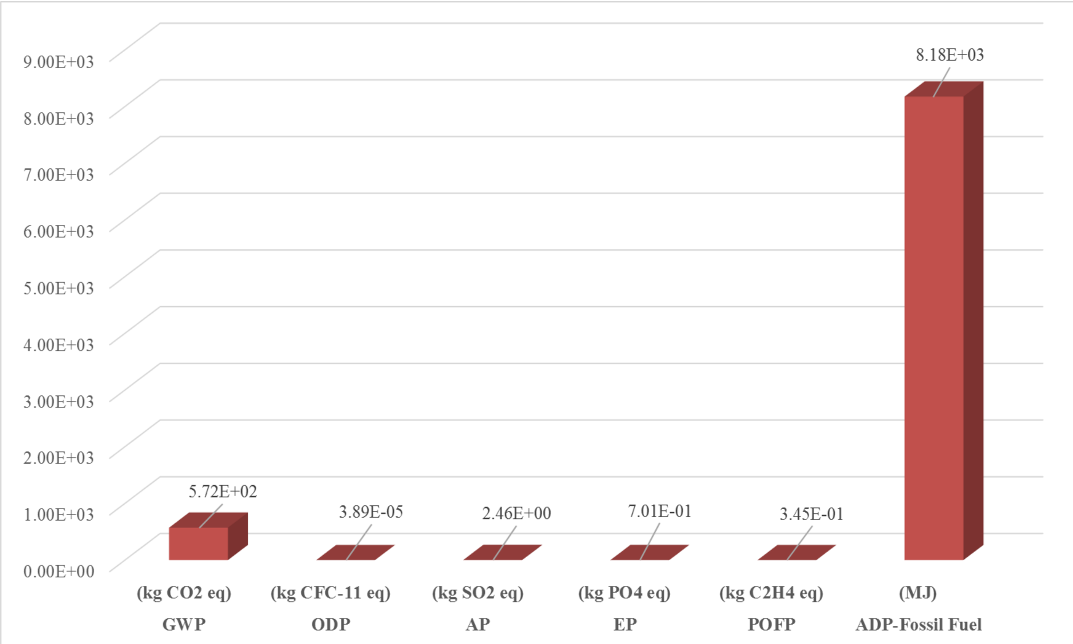

Figure 4.7. Total characterization results of the case study building in One Click LCA

4.2. SimaPro Results

4.2.1. LCA of Case Study Building by Using SimaPro (1)

As it was mentioned before, two life cycle assessments were conducted for the case study building having different system boundaries as shown in Table 3.1 in Sec 3.2.1. Therefore, results are differentiated from each other due to the discrepancies in life-cycle stages. Results of the one done for the comparison with One Click LCA are represented below. Detailed characterization and normalization results including per product/material is given in Appendix B.

Figure 4.8 represents GWP characterization results of the case study building in SimaPro (1). Building elements that have primary impacts on GWP were ranked as photovoltaic panels (1.40E+02 kg CO_2 eq), concrete (9.52E+01 kg CO_2 eq), aluminium composite panel (6.59E+01 kg CO_2 eq), structural steel (6.49E+01 kg CO_2 eq), aluminium window frame (6.16E+01 kg CO_2 eq), reinforcing steel (5.67E+01 kg CO_2 eq), galvanized steel sheet (1.72E+01 kg CO_2 eq) and triple glazed windows (1.68E+01 kg CO_2 eq). Total GWP was calculated as 5.64E+02 kg CO_2 eq.

Figure 4.9 represents ODP characterization results. Photovoltaic panels (2.27E-05 kg CFC-11 eq) were again found to be the dominant element in ODP results. Other elements are (4.88E-06 kg CFC-11 eq), concrete (4.70E-06 kg CFC-11 eq), structural steel (3.34E-06 kg CFC-11 eq), reinforcing steel (3.02E-06 kg CFC-11 eq), aluminum window frame (2.22E-06 kg CFC-11 eq) and triple glazed window (1.27E-06 kg CFC-11 eq). Total ODP was measured as 4.56E-05 kg CFC-11 eq.

Figure 4.10 represents AP characterization results of the case study building in SimaPro (1). Likewise GWP results, most contributing building components in AP were ranked as photovoltaic panels (7.39E-01 kg SO_2 eq), aluminum composite panels (3.83E-01 kg SO_2 eq), aluminum window frame (3.53E-01 kg SO_2 eq), structural steel (3.08E-01 kg SO_2 eq), reinforcing steel (2.43E-01 kg SO_2 eq), concrete (2.12E-01 kg SO_2 eq) and triple glazed window (1.23E-01 kg SO_2 eq). Total AP was determined as 2.66E+00 kg SO_2 eq.

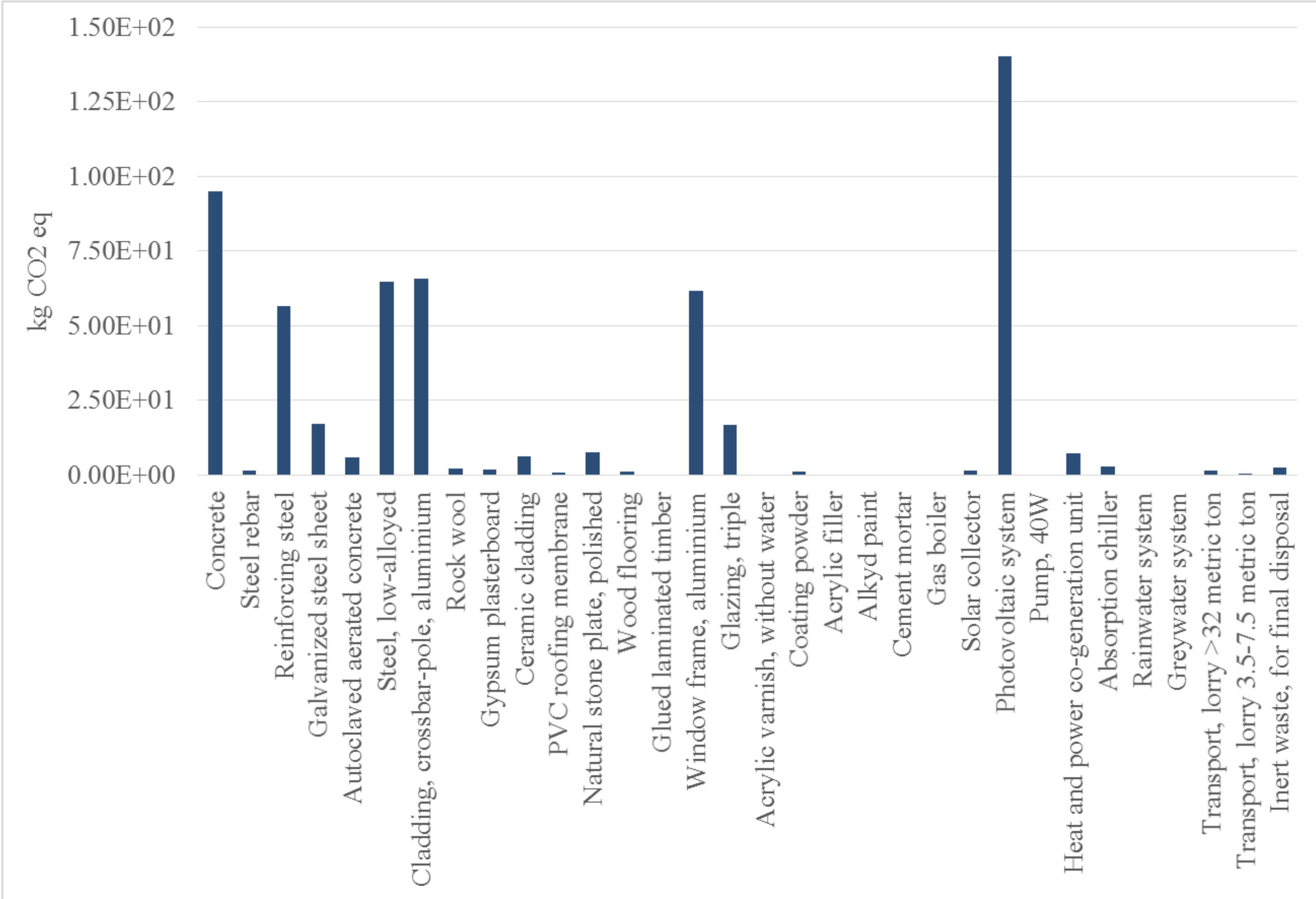

Figure 4.8. GWP characterization results of the case study building in SimaPro (1)

Figure 4.9. ODP characterization results of the case study building in SimaPro *(1)*

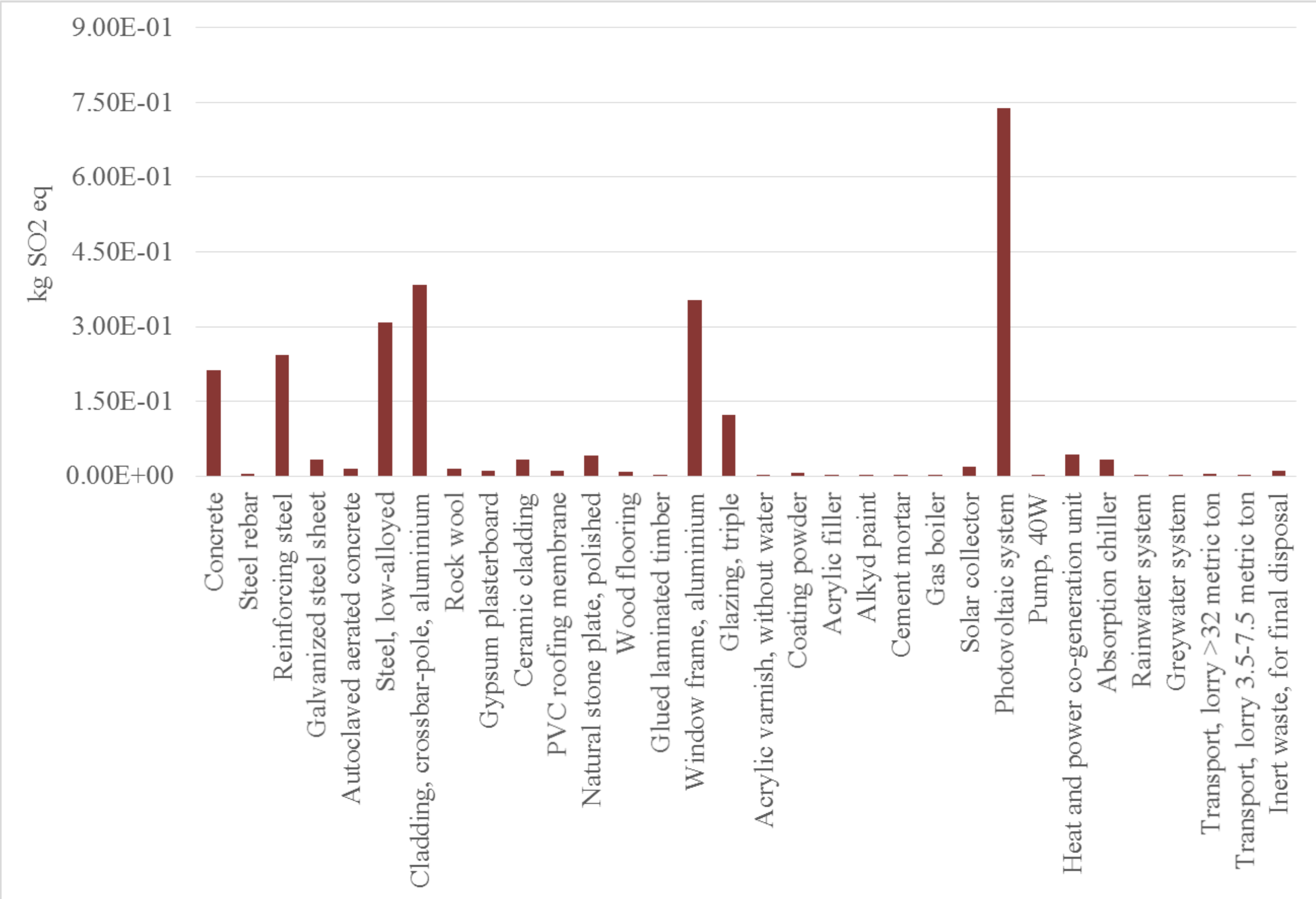

Figure 4.10. AP characterization results of the case study building in SimaPro (1)

According to EP characterization results shown in Figure 4.11, it was found that photovoltaic panels (2.98E-01 kg PO_4 eq), structural steel (2.18E-01 kg PO_4 eq), reinforcing steel (1.18E-01 kg PO_4 eq), aluminum composite panel (1.06E-01 kg PO_4 eq), aluminum window frame (8.38E-02 kg PO_4 eq) and concrete (6.03E-02 kg PO_4 eq) have drastic impacts. On the other hand, galvanized steel sheet had positive effect on building's life-cycle. Total EP was measured as 9.73E-01 kg PO_4 eq.

With regard to the POFP (Figure 4.12), photovoltaic panels (3.43E-02 kg C_2H_4 eq), structural steel (3.43E-02 kg C_2H_4 eq), reinforcing steel (3.41E-02 kg C_2H_4 eq), aluminium composite panel (2.57E-02 kg C_2H_4 eq) and aluminium window frame (2.19E-02 kg C_2H_4 eq) showed quite close results. They were followed by concrete (9.07E-03 kg C_2H_4 eq), galvanized steel sheet (5.28E-03 kg C_2H_4 eq) and triple glazed windows (4.46E-03 kg C_2H_4 eq). Total POFP was calculated as 1.83E-01 kg C_2H_4 eq.

Similar to other impact categories, photovoltaic panels (1.60E+03 MJ) dominates the ADP-fossil fuel results, as indicated in Figure 4.13. Moreover, aluminium composite panel (7.01E+02 MJ), structural steel (6.40E+02 MJ), aluminium window frame (5.97E+02 MJ), concrete (5.63E+02 MJ), reinforcing steel (5.49E+02 MJ), triple glazed windows (1.89E+02 MJ) and galvanized steel sheet (1.75E+02 MJ) were found to be significant elements on ADP-fossil fuel. Total ADP-fossil fuel was determined as 5.53E+03 MJ.

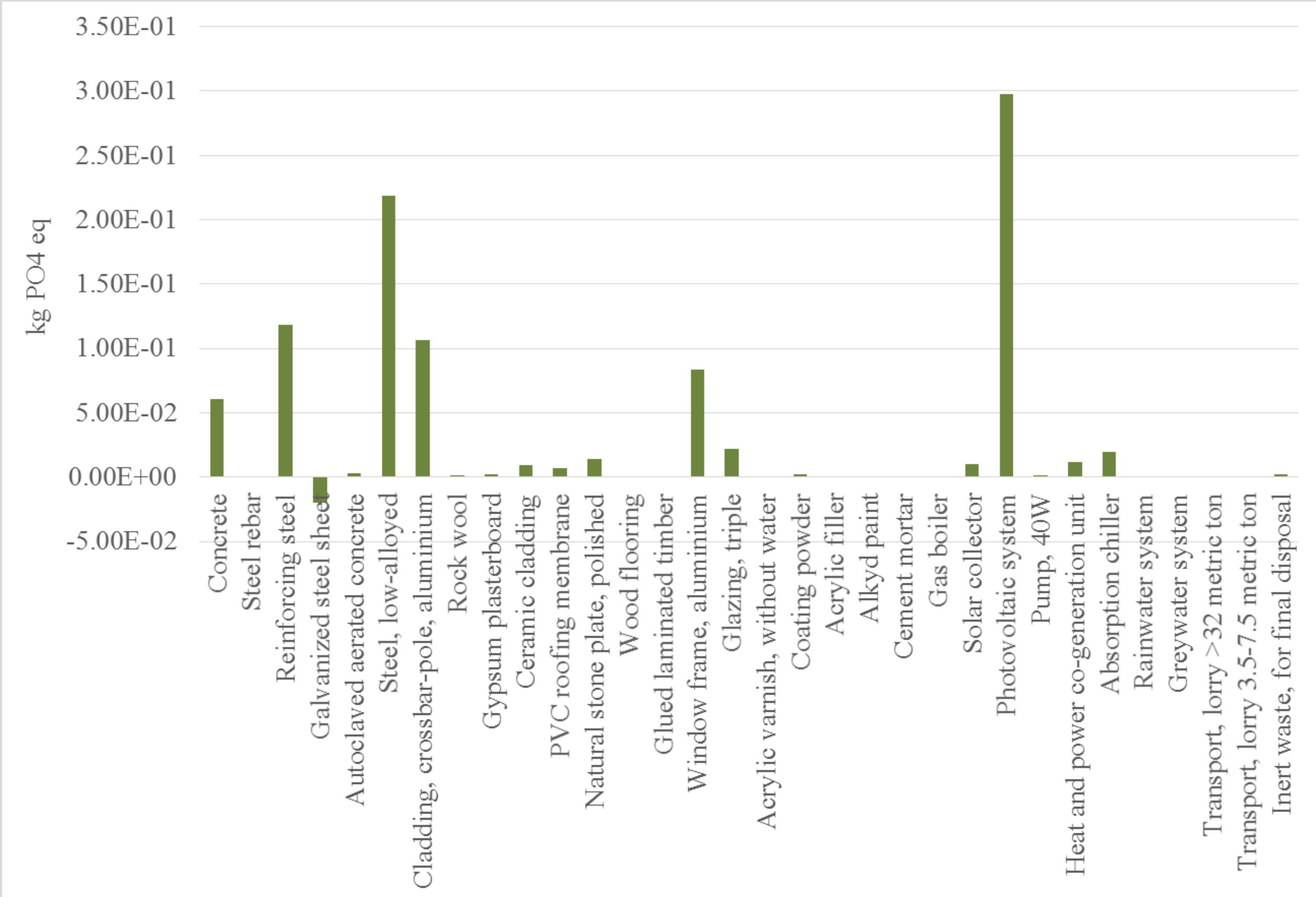

Figure 4.11. EP characterization results of the case study building in SimaPro (1)

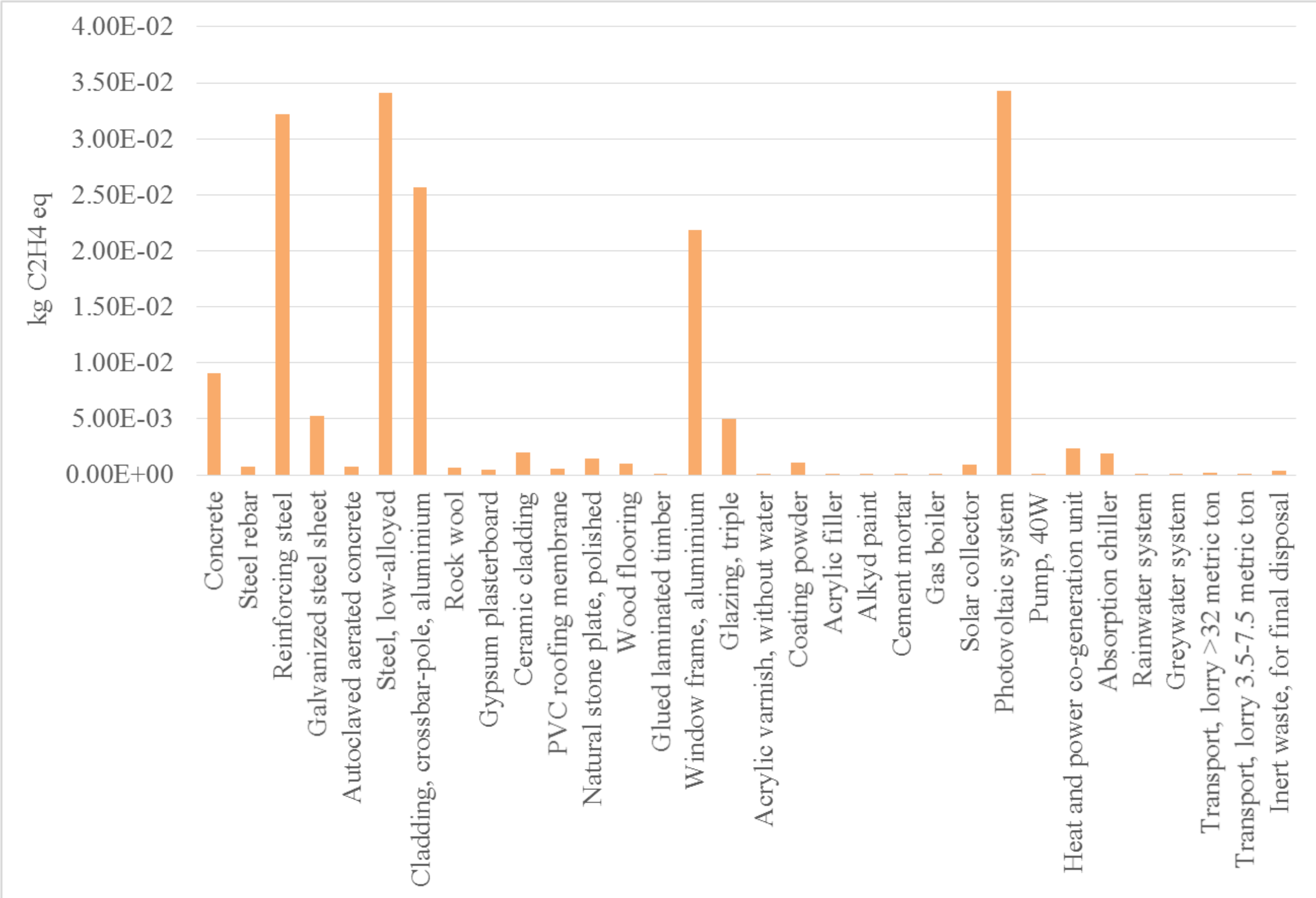

Figure 4.12. POFP characterization results of the case study building in SimaPro (1)

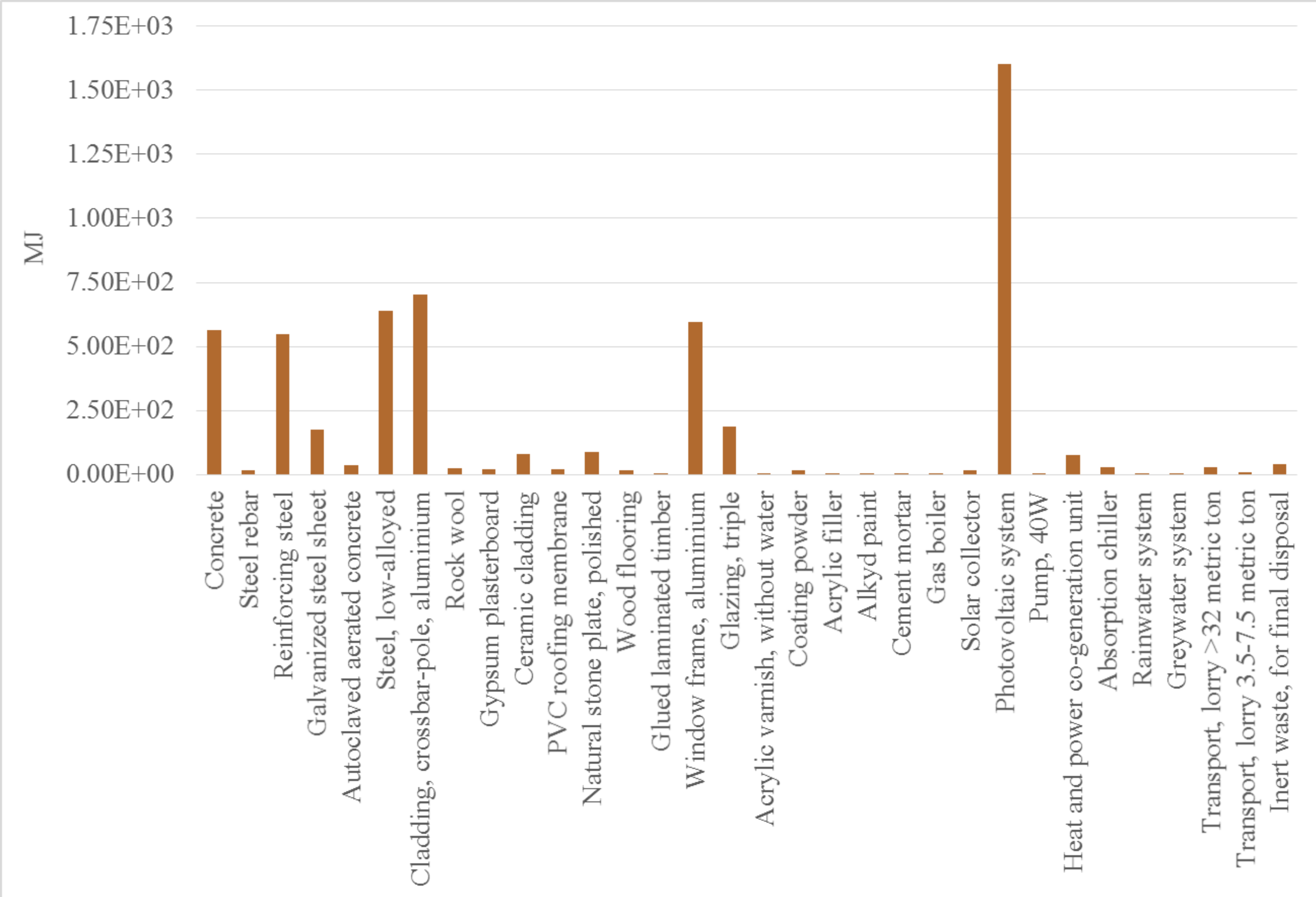

Figure 4.13. ADP-Fossil fuel characterization results of the case study building in SimaPro (1)

The summary of the characterization results of the case study building in SimaPro (1) is provided in Figure 4.14. In order to understand how much impact a specific category causes compared to the others, a normalization graph is also provided (Figure 4.15). According to the normalization results as shown in Figure 4.15, GWP and ADP-Fossil fuel impacts were found to be quite close to each other by having 1.47E-11 and 1.66E-11, respectively. They are followed by AP (1.20E-11), EP (6.42E-12) and POFP (5.17E-12). The least impact was observed in ODP results with the value of 2.44E-13.

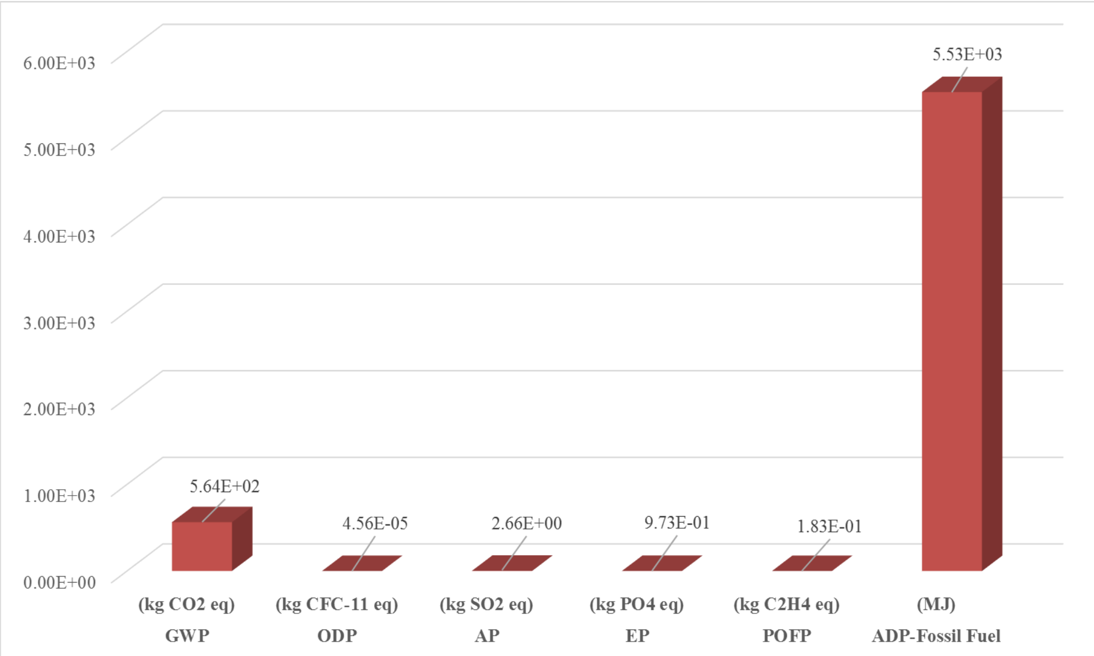

Figure 4.14. Total characterization results of the case study building in SimaPro (1)

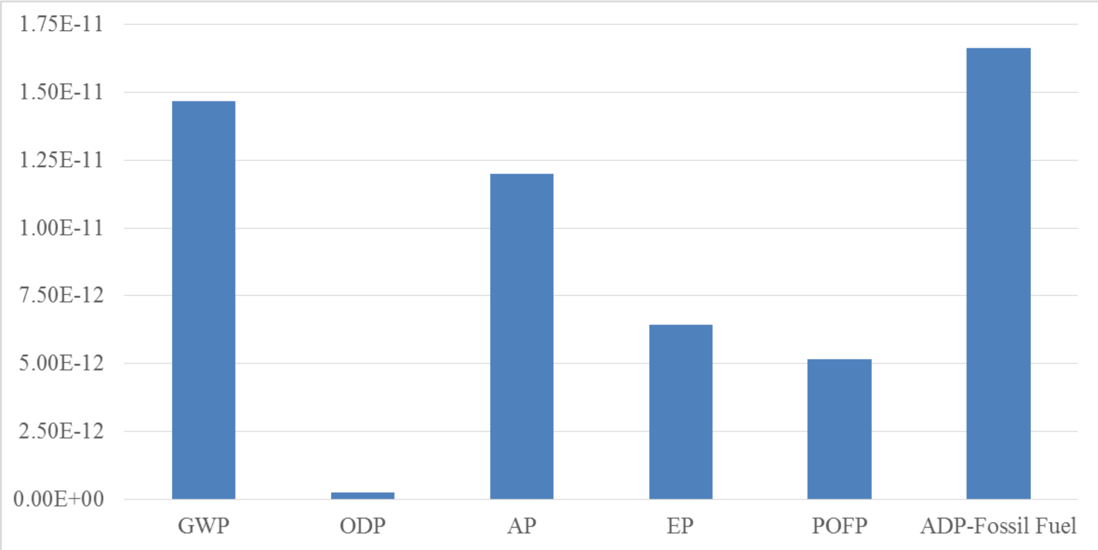

Figure 4.15. Normalization results of the case study building in SimaPro (1)

4.2.2. LCA of the Baseline Building by Using SimaPro

LCA of the baseline building was only conducted by using SimaPro since One Click version that was used for the study did not include the tabs for energy and water use. Due to this reason, it was thought that a study intended to compare baseline building both in SimaPro and One Click LCA would not be consistent and fair. Therefore, only SimaPro was used for the assessment of the baseline building. Detailed characterization and normalization results including per product/material are provided in Appendix C.

According to the characterization results of the baseline building, it can be seen from Figure 4.16 – 4.22 that prevalent components were operational natural gas and electricity use in all impact categories. As it can be seen from Figure 4.16 which shows GWP characterization results of the baseline building in SimaPro, for GWP, electricity (3.46E+03 kg CO_2 eq) has the most striking impact. Following this, natural gas in operational use (3.01E+02 kg CO_2 eq), concrete (9.52E+01 kg CO_2 eq), aluminum composite panel (6.67E+01 kg CO_2 eq), structural steel (6.67E+01 kg CO_2 eq) and reinforcing steel (5.59E+01 kg CO_2 eq) showed limited impacts on GWP. Total GWP was measured as 4.12E+03 kg CO_2 eq.

In case of ODP, electricity and natural gas use changed their rankings by 6.39E-05 kg CFC-11 eq and 2.34E-04 kg CFC-11 eq, respectively (Figure 4.17). The same building components which are concrete (4.70E-06 kg CFC-11 eq), aluminum composite panel (4.92E-06 kg CFC-11 eq), structural streel (3.62E-06 kg CFC-11 eq) and reinforcing steel (3.39E-06 kg CFC-11 eq) represent slight impacts on ODP. Total ODP was calculated as 3.19E-04 kg CFC-11 eq.

According to the AP results, electricity had a characterization value of 1.90E+01 kg SO_2 eq while natural gas, structural steel, aluminum composite panel, reinforcing steel and concrete had 1.39E+00 kg SO_2 eq, 3.87E-01 kg SO_2 eq, 2.59E-01 kg SO_2 eq and 2.12E-01 kg SO_2 eq, respectively. Total AP was determined as 2.19E+01 kg SO_2 eq (Figure 4.18)

Figure 4.16. GWP characterization results of the baseline building in SimaPro

Figure 4.17. ODP characterization results of the baseline building in SimaPro

Figure 4.18. AP characterization results of the baseline building in SimaPro

Electricity use dominated all EP results with a characterization value of 1.02E+01 kg PO_4 eq. Total EP was measured as 1.10E+01 kg PO_4 eq (Figure 4.19).

Figure 4.20 depicts POFP characterization results of the baseline building in SimaPro. Total POFP was calculated as 9.95E-01 kg C_2H_4 eq. It was mostly shared by electricity (7.56E-01 kg C_2H_4 eq), natural gas (1.06E-01 kg C_2H_4 eq), structural steel (3.75E-02 kg C_2H_4 eq), reinforcing steel (3.61E-02 kg C_2H_4 eq) and aluminum composite panel (2.69E-02 kg C_2H_4 eq).

ADP-Fossil fuel characterization results of the baseline building obtained via SimaPro are presented in Figure 4.21. As expected, electricity and natural gas had the most significant impacts on ADP-fossil fuel by 4.26E+04 MJ and 1.55E+04 MJ, respectively. Aluminum composite panel (7.24E+02 MJ), structural steel (7.05E+02 MJ), reinforcing steel (6.27E+02 MJ) and concrete (5.63E+02 MJ) may also be considered as minor contributors.

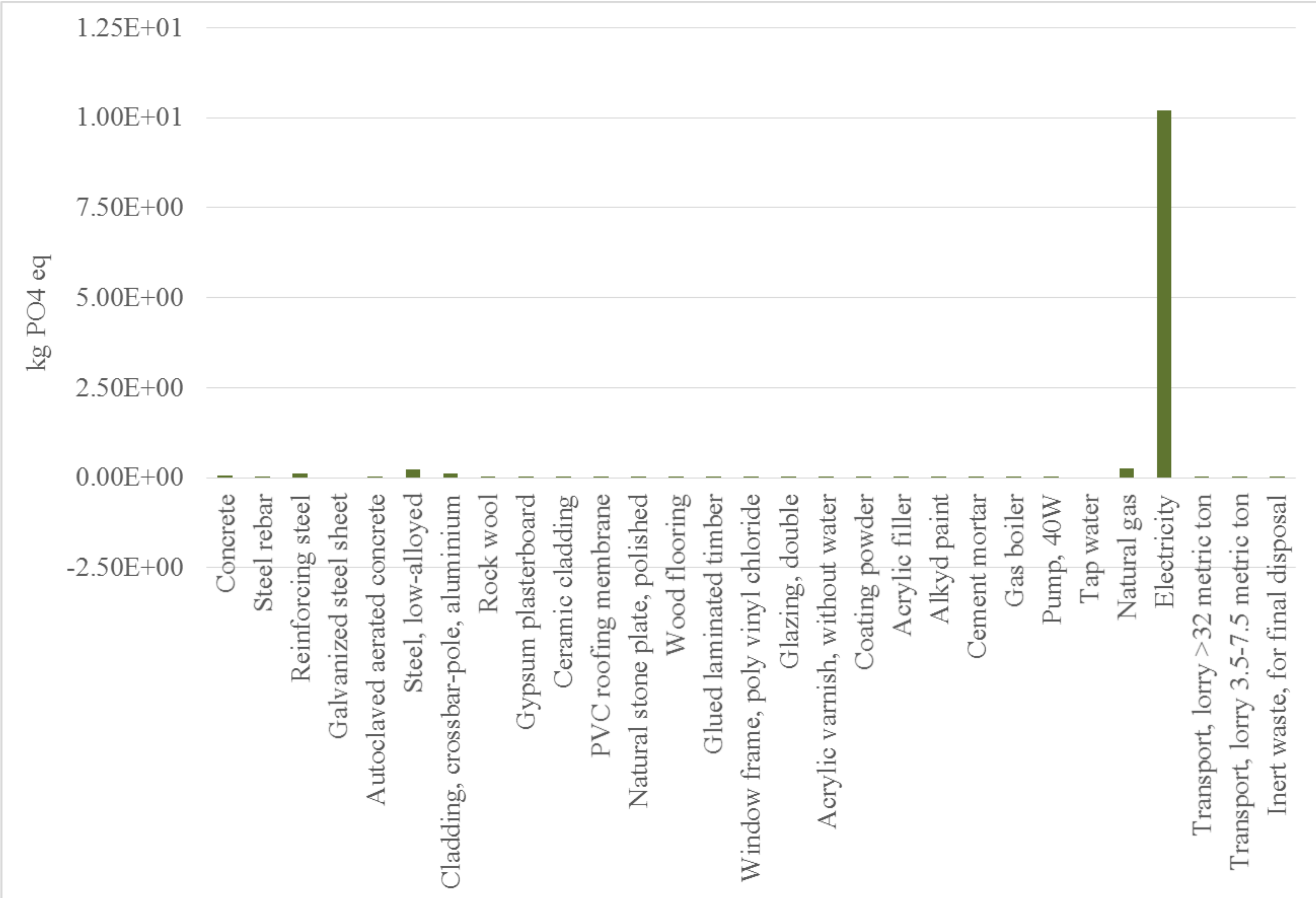

Figure 4.19. EP characterization results of the baseline building in SimaPro

Figure 4.20. POFP characterization results of the baseline building in SimaPro

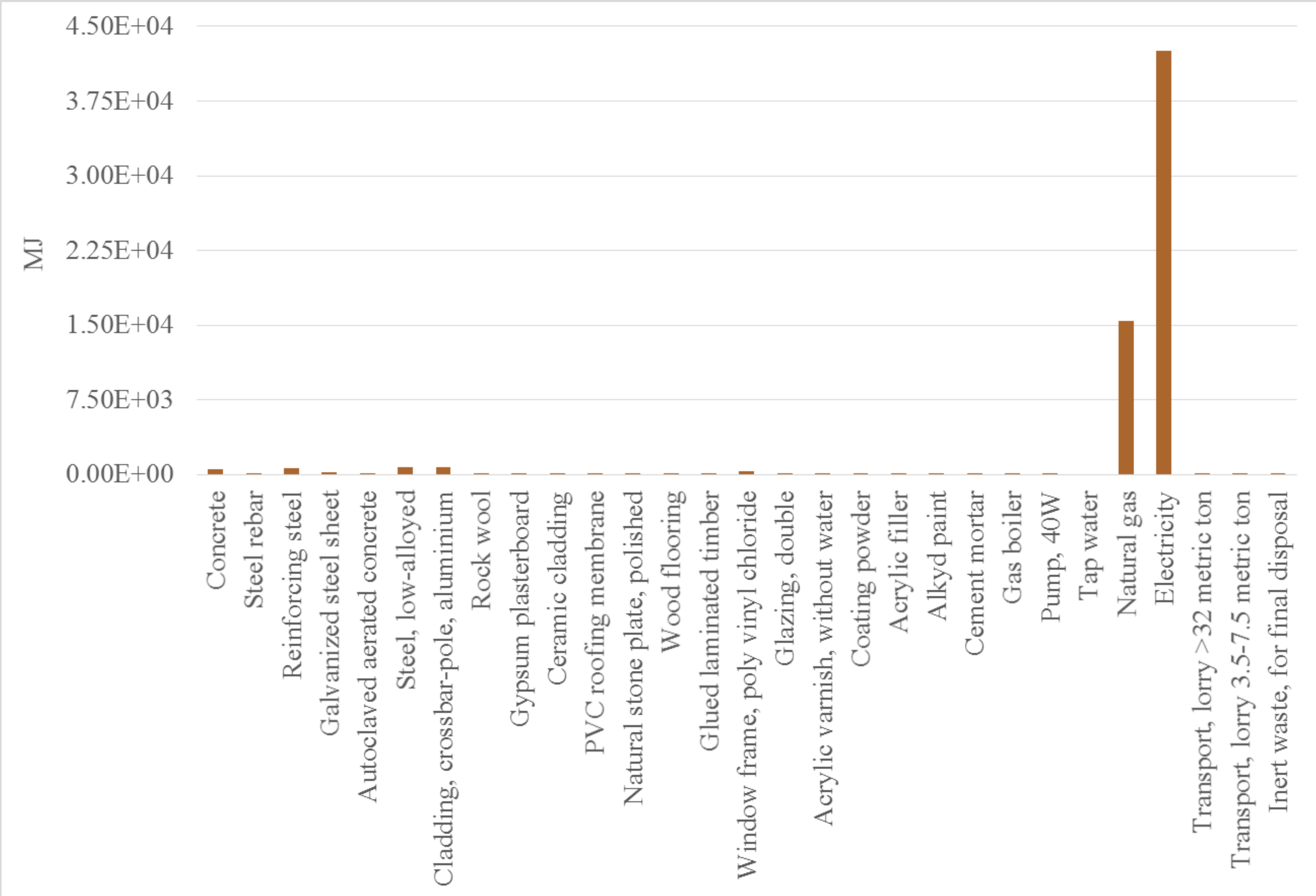

Figure 4.21. AD*P*-Fossil fuel characterization results of the baseline building in SimaPro

Figure 4.22 depicts the total characterization results of the baseline building in SimaPro. When normalized impacts of the baseline building (Figure 4.23) are concerned in an attempt to compare the impact results, it shows that ADP-fossil fuel (1.62E-10) had the higher results. After that, the ranking was followed as GWP (9.86E-11), AP (9.19E-11), EP (6.97E-11), POFP (2.71E-11) and ODP (1.41E-12).

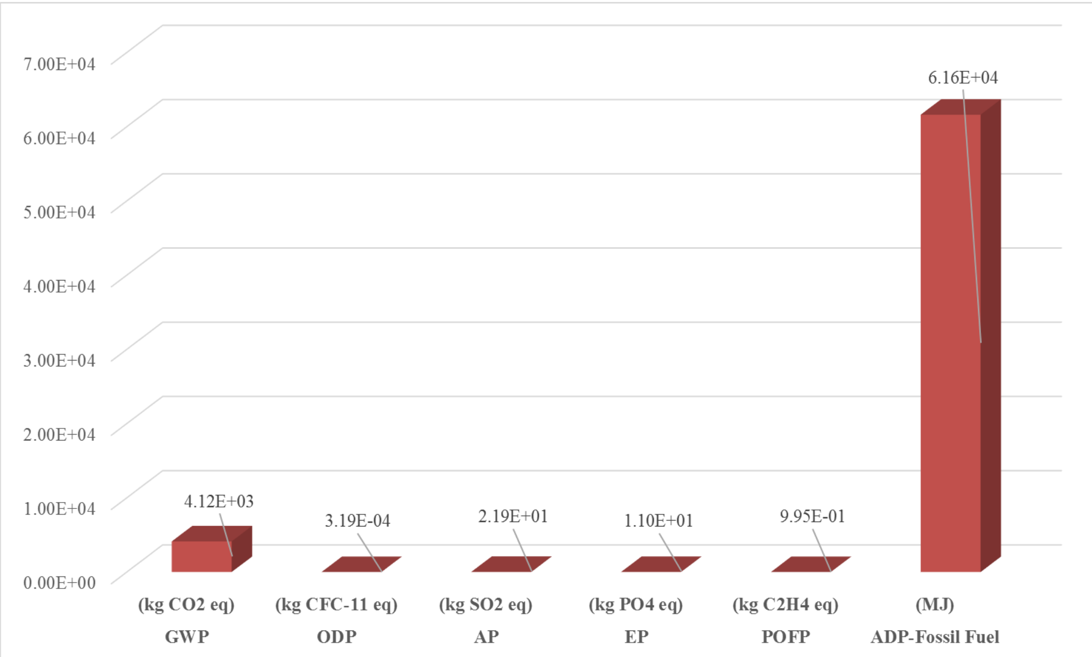

Figure 4.22. Total characterization results of the baseline building in SimaPro

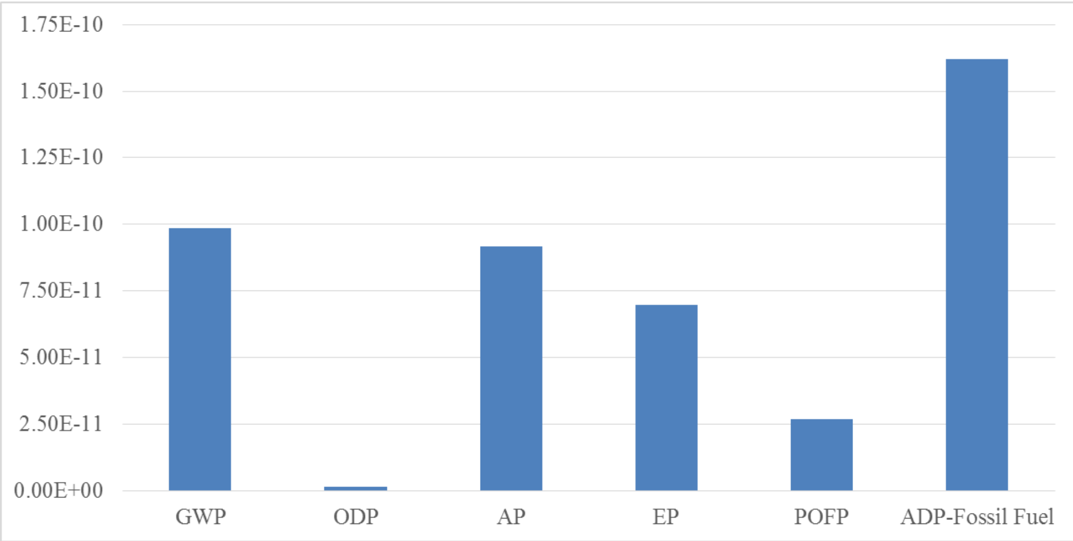

Figure 4.23. Normalization results of the baseline building in SimaPro

4.2.3. LCA of Case Study Building by Using SimaPro (2)

Case study building characterization results obtained from SimaPro 8.4.1.0 via CML IA Baseline method are demonstrated below. Detailed characterization and normalization tables are given in Appendix D.

Figure 4.24 shows GWP characterization results of the case study building in SimaPro (2). According to the GWP characterization results, most contributing elements are seen as natural gas in operational use (2.59E+02 kg CO_2 eq), photovoltaic panels (1.40E+02 kg CO_2 eq), concrete (9.52E+01 kg CO_2 eq), aluminum composite panel (6.59E+01 kg CO_2 eq), structural steel (6.49E+01 kg CO_2 eq), aluminum window frame (6.16E+01 kg CO_2 eq), reinforcing steel (5.67E+01 kg CO_2 eq), steel sheets (1.72E+01 kg CO_2 eq) and triple glazed windows (1.68E+01 kg CO_2 eq). On the other hands, recycling of aluminum (-6.77E+00 kg CO_2 eq) and steel (-1.25E+02 kg CO_2 eq) after demolition serves a significant positive impact on building's life-cycle. Total characterization result of the case study building for GWP was calculated as 6.91E+02 kg CO_2 eq.

With regard to the OPD, natural gas in operational use dominates the results with a considerable difference (2.02E-04 kg CFC-11 eq), as shown in Figure 4.25. Photovoltaic panels used in the building (2.27E-05 kg CFC-11 eq) may be considered as the second important element affecting OPD results. Total ODP result was found as 2.42E-04 kg CFC-11 eq.

Figure 4.26 shows AP characterization results of the case study building in SimaPro (2). AP results has similarities with GWP results although there are slight numerable variations. Natural gas in operational use (1.20E+00 kg SO_2 eq), photovoltaic panels (7.39E-01 kg SO_2 eq), aluminum composite panel (3.83E-01 kg SO_2 eq), aluminum window frame (3.53E-01 kg SO_2 eq), structural steel (3.08E-01 kg SO_2 eq), reinforcing steel (2.43E-01 kg SO_2 eq), concrete (2.12E-01 kg SO_2 eq) and triple glazed windows (1.23E-01 kg SO_2 eq) were found to be important components having higher impacts on AP. Recycling of aluminum (-3.99E-02 kg SO_2 eq) and steel (-5.03E-01 kg SO_2 eq) again showed positive impacts. Total AP of the case study building was calculated as 3.31E+00 kg SO_2 eq.

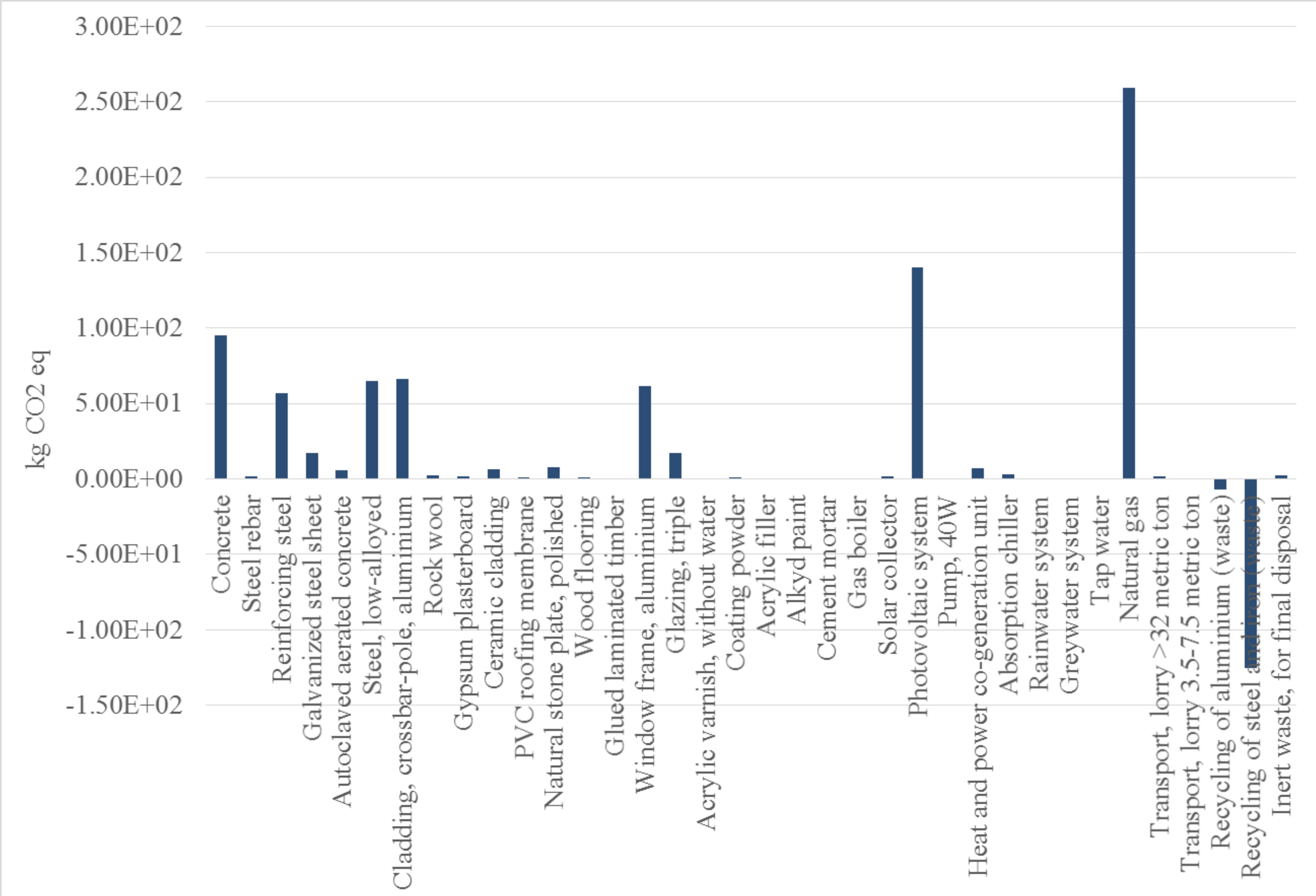

Figure 4.24. GWP characterization results of the case study building in SimaPro (2)

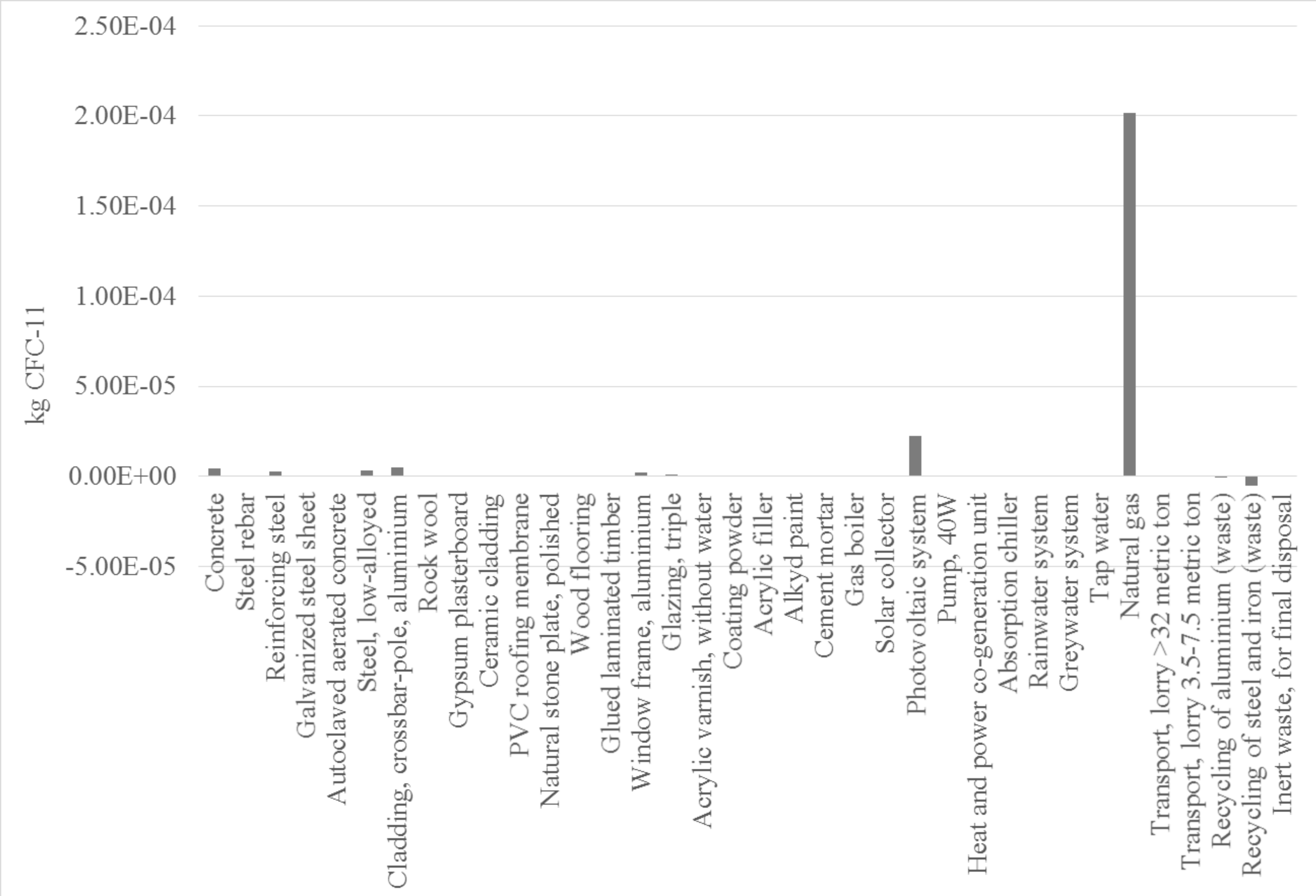

Figure 4.25. ODP characterization results of the case study building in SimaPro (2)

Figure 4.26. AP characterization results of the case study building in SimaPro (2)

Figure 4.27 shows EP characterization results of the case study building in SimaPro (2). Although most contributing components were obtained similar with GWP and AP, ranking of them changes in EP results. Accordingly, it was seen that photovoltaic panels (2.98E-01 kg PO_4 eq), natural gas in operational use (2.19E-01 kg PO_4 eq), structural steel (2.18E-01 kg PO_4 eq), reinforcing steel (1.18E-01 kg PO_4 eq), aluminum composite panel (1.06E-01 kg PO_4 eq), aluminum window frame (8.38E-02 kg PO_4 eq), concrete (6.03E-02 kg PO_4 eq), triple glazing window (2.22E-02 kg PO_4 eq) and absorption chiller (1.98E-02 kg PO_4 eq) affects EP more than other building elements. On the other hand, galvanized steel sheet (-2.00E-02 kg PO_4 eq) showed avoided impacts together with aluminum (-8.98E-03 kg PO_4 eq) and steel (-1.50E-01 kg PO_4 eq) recycling. Total EP of case study building was obtained as 1.03E+00 kg PO_4 eq.

Figure 4.28 represents POFP characterization results of the case study building in SimaPro (2). For POFP, natural gas in operational use (9.13E-02 kg C_2H_4 eq) was observed as the dominant component followed by photovoltaic panels (3.43E-02 kg C_2H_4 eq), structural steel (3.41E-02 kg C_2H_4 eq), reinforcing steel (3.22E-02 kg C_2H_4 eq), aluminum composite panel (2.57E-02 kg C_2H_4 eq), aluminum window frame (2.19E-02 kg C_2H_4 eq) and concrete (9.07E-03 kg C_2H_4 eq). Recycling of steel (-8.42E-02 kg C_2H_4 eq) showed a quite significant positive effect. Total characterization result for POFP was calculated as 1.87E-01 kg C_2H_4 eq.

In case of ADP-Fossil fuel, natural gas in operational use (1.33E+04 MJ) was found to be the most contributing component, as expected (Figure 4.29). Although they were not comparable, it was followed by photovoltaic panels (1.60E+03 MJ), aluminum composite panels (7.01E+02 MJ), structural steel (6.40E+02 MJ), aluminum window frame (5.97+02 MJ), concrete (5.63E+02 MJ) and reinforcing steel (5.49+02 MJ). Recycling of aluminum and steel avoided -5.89E+01 MJ and -1.12E+03 MJ, respectively. Total ADP-fossil fuel characterization result was 1.77E+04 MJ.

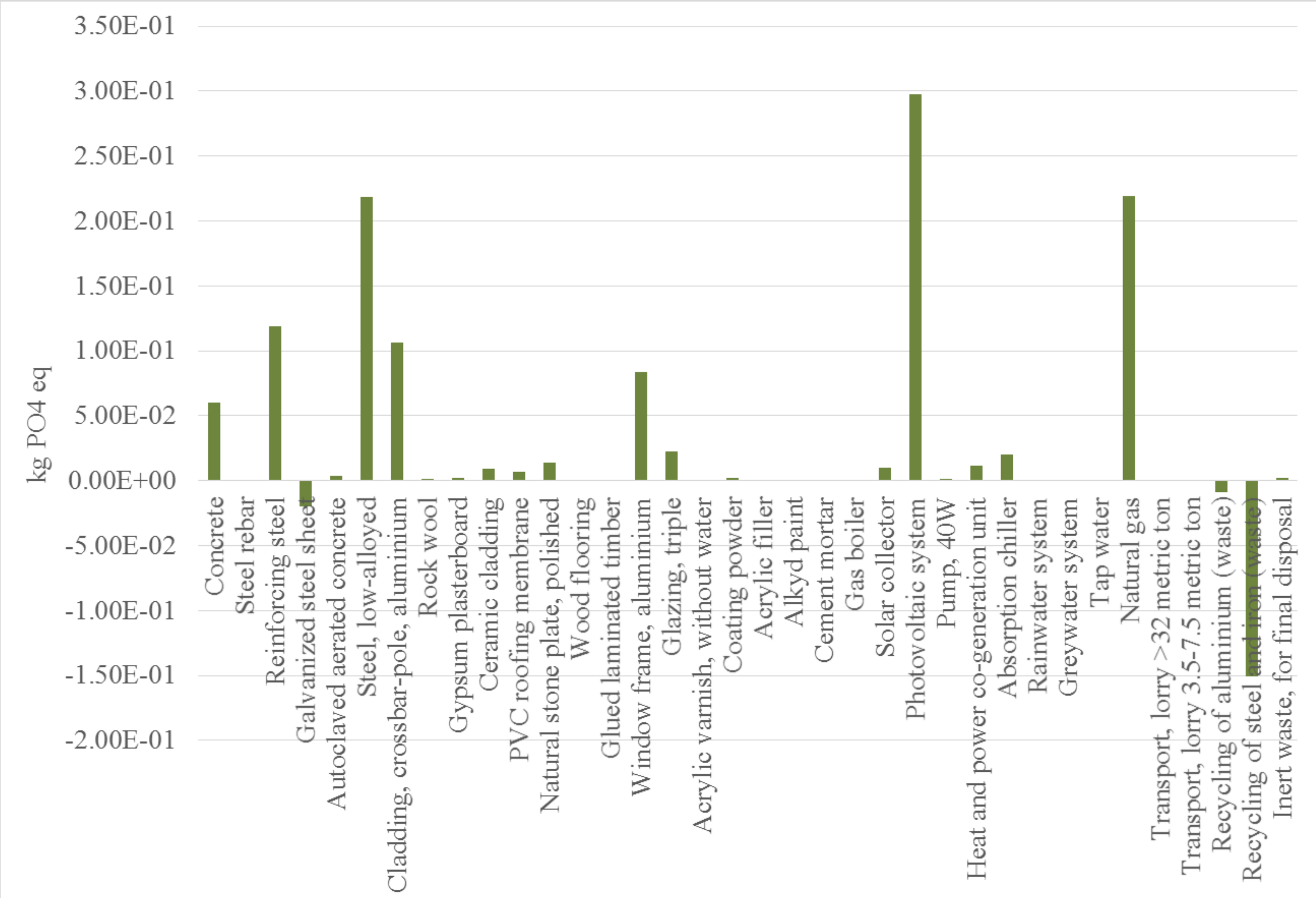

Figure 4.27. EP characterization results of the case study building in SimaPro (2)

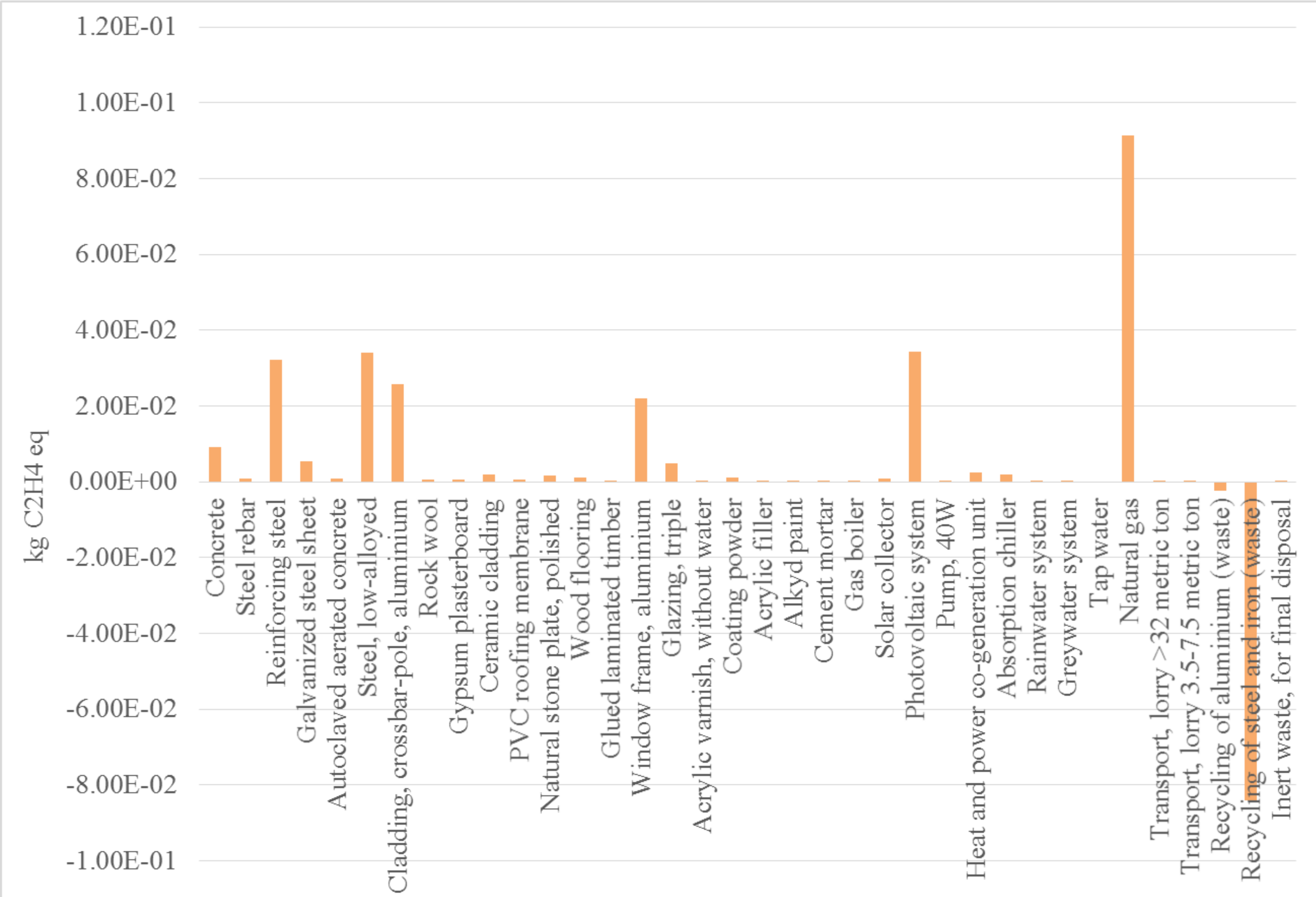

Figure 4.28. POFP characterization results of the case study building in SimaPro (2)

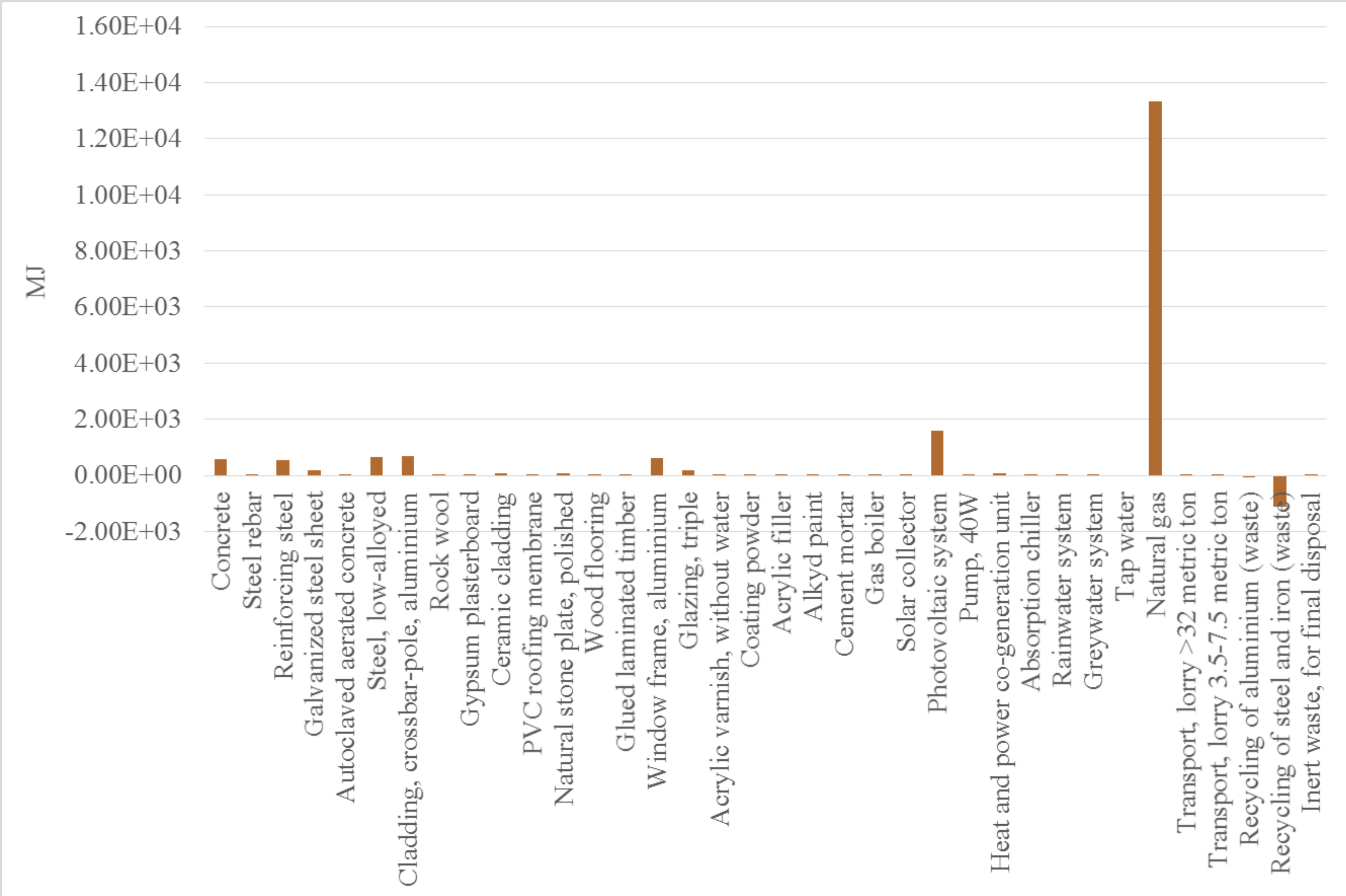

Figure 4.29. ADP-Fossil fuel characterization results of the case study building in SimaPro (2)

Total characterization and normalization results of the case study building in SimaPro (2) are presented in Figure 4.30 and 4.31, respectively. According to the normalized results, impact category of ADP-Fossil Fuels has the most significant effects on the building's life-cycle with a normalized result of 4.20E-11 while ODP results represent the least contributing impacts by having 9.63E-13. Other four categories which are GWP, AP, EP and POFP are seen to be close and relatively comparable to each other with the values of 1.29E-11, 1.03E-11, 4.37E-12 and 4.01E-12, respectively.

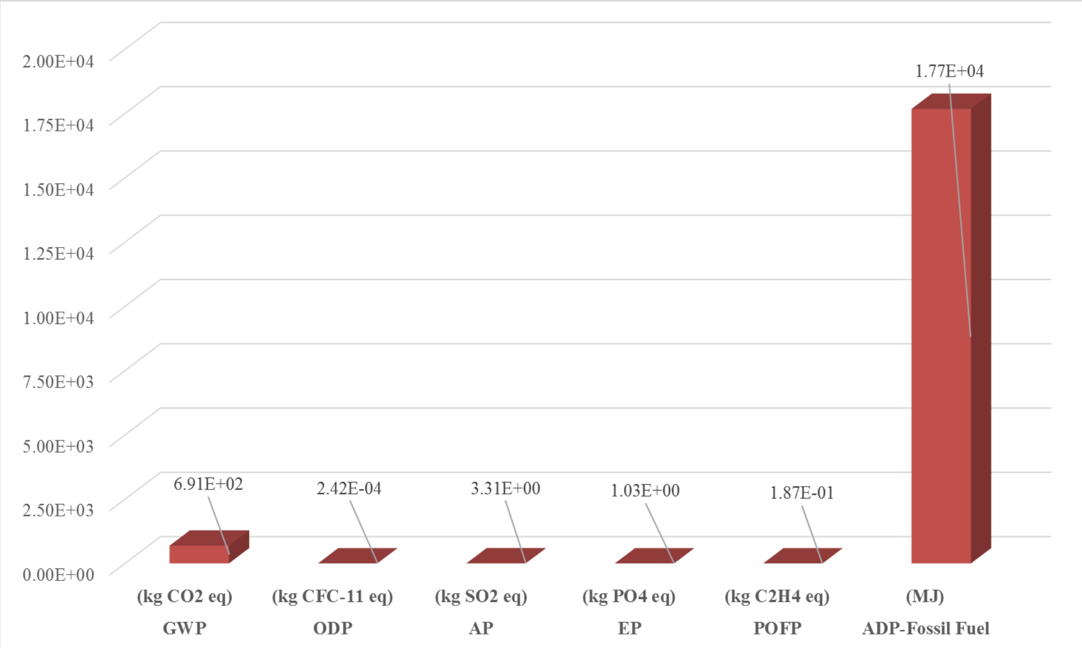

Figure 4.30. Total characterization results of the case study building in SimaPro (2)

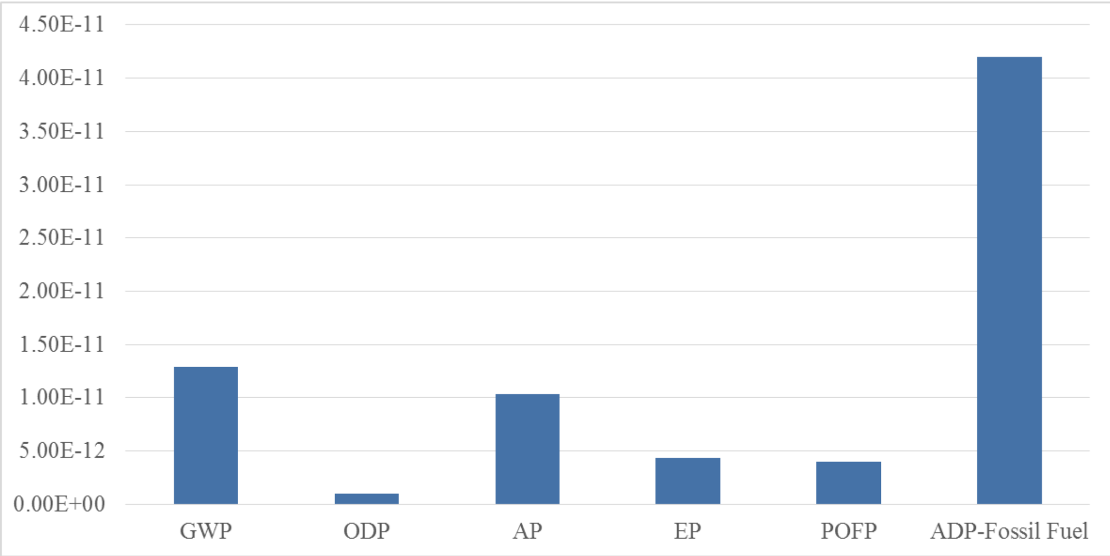

Figure 4.31. Normalization results of the case study building in SimaPro (2)

4.3. Discussion

4.3.1. Comparison of One Click LCA and SimaPro Results

Since One Click LCA does not give normalization results, comparison of the results could be done only on characterization basis which is one of the main differences between both programs. Figure 4.32 – Figure 4.34 show the comparison of the characterization results of both One Click LCA and SimaPro in each impact category.

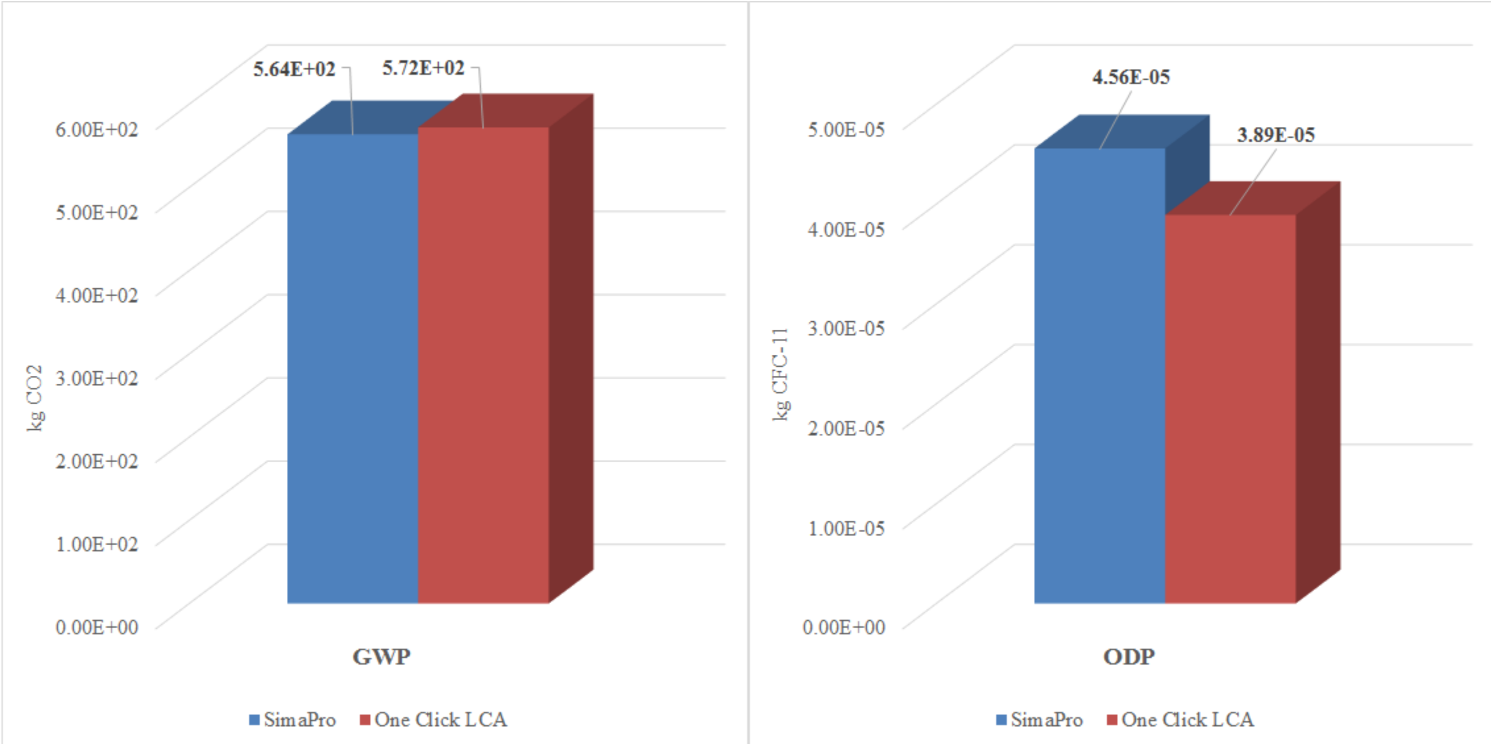

Figure 4.32. Comparison of GWP and ODP characterization results of One Click LCA and SimaPro (1) for the case study building

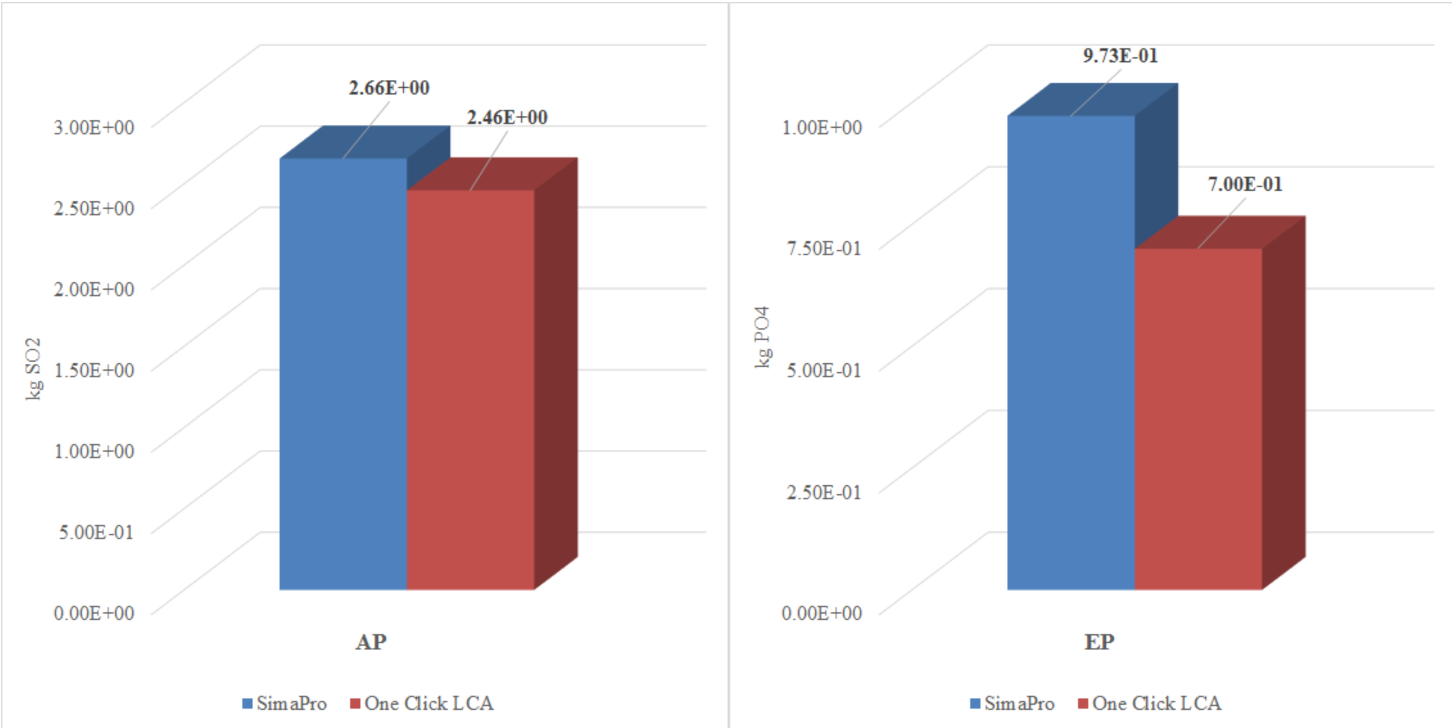

Figure 4.33. Comparison of AP and EP characterization results of One Click LCA and SimaPro (1) for the case study building

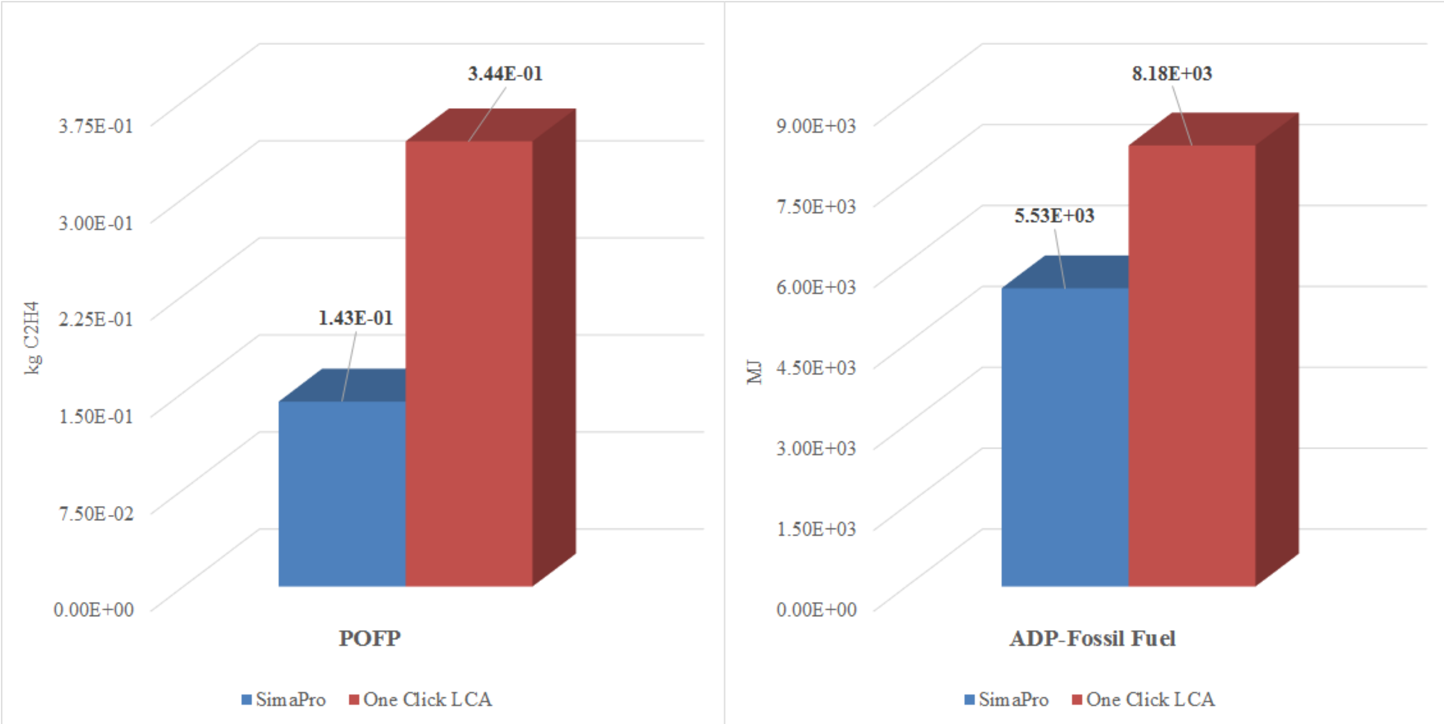

Figure 4.34. Comparison of POFP and ADP-Fossil fuel characterization results of One Click LCA and SimaPro (1) for the case study building

As shown in these graphs, the results were highly comparable in each impact category, except for POFP and ADP-Fossil fuel. Although the reason for having comparable results in remaining impact categories may be using mostly the same database which is Ecoinvent and also the same impact method that is CML, there might be several reasons for the discrepancies observed. Since there was no study in the literature on the comparison of One Click LCA and SimaPro before, it is very hard to find what may cause the difference between the results of POFP and ADP, but the main reason might be the difference in system boundaries. As it is mentioned in Sec 3.2.1.1, Refurbishment (B5) stage was not included in SimaPro due to lack of data while One Click LCA automatically takes it into account, which probably makes it the main reason for the difference of 32% higher result in ADP-Fossil fuel impact category. According to the EN 15978 standard, refurbishment is exemplified as "a major change of the internal layout (partitioning), a change of the technical system related to heating and/or modification for the purpose of a […] change of use". In other words, refurbishment refers to a holistic and deep modification which can affect main building components and modify building functions and performance (European Commission, 2012) Therefore, while doing refurbishment, considerable amount of energy is consumed for partial deconstruction, re-installation, major renovations, transport to the site, etc. (Hong et al., 2015). When Table 4.1 that shows One Click LCA results according to the life-cycle stages is analyzed, it can be seen that Replacement (B4) and Refurbishment (B5) stages are responsible for 1.95E+07 MJ total ADP- Fossil fuel value which means 1.67E+03 MJ for per m^2 of the building area. Although it also includes the impacts of B4 stage and the practitioner cannot allocate the total impact based on life-cycle stages, the effect of B4 is assumed to be quite less than B5 stage due to the majority of possible changes included by B5 as stated in EN Standards (European Commission, 2012). Hence, as a result, ADP-Fossil fuel results of One Click LCA and SimaPro gets quite comparable when the impact of 1.67E+03 MJ is omitted. At this juncture, it is important to note that although refurbishment is done in order to enhance use-phase building performance which may decrease during the life-time of the building, the effect of it on the operational energy use cannot be seen from the results since Operational Energy Use (B6) stage does not included in the system boundary. By way of explanation, the higher results in ADP-Fossil fuel only shows the effect of the energy consumed during refurbishment process and does not indicate the effect of the energy improvements after refurbishment in building's life time.

On the other hand, organic chemicals such as VOCs that are the main reasons for POFP are released during these refurbishment activities. The level of VOC in newly constructed or refurbished buildings is known to be high due to the building materials and furnishings leading high concentrations of VOC (Torgal et al., 2013). Therefore, refurbishment activities that will take place during 60 years of the life time of the building may probably increase the POFP results by 58% as One Click LCA forsees. Table 4.1 presents total POFP values of B4 and B5 stages as 6.19E+02 kg C_2H_4 eq resulting in 5.28E-02 kg C_2H_4 eq per m^2 floor area. Similar to ADP-Fossil fuel calculations, omitting the rough value of 5.28E-02 kg C_2H_4 eq makes POFP results of both One Click LCA and SimaPro comparable.

Another reason can be the variation in data inventories. As can be seen from Table 3.3, data inventories of both LCAs were slightly different due to the availability of data in each program. Data inventories of the programs were not 100% same with each other since proper material or product could not be found in some cases. Therefore, the choice of the reference material may affect the intensity of the results. Moreover, one other reason might be the difference in geographic data quality requirements. While One Click LCA mostly used EPD data from Europe, data of the LCA in SimaPro had to be chosen as global scale due to data availability. This may also pose a deviation in the results.

Another difference between the programs is the representation way of the results. One Click LCA also gives graphs according to the life cycle stages. However, it is not possible to see how much impact one material or product causes during each life cycle stage in SimaPro. Although graphs showing results in some of the life cycle stages could be prepared by the LCA practitioner by hand by using detailed excel reports given by SimaPro, some stages could not be shown such as maintenance and replacement since the replacement amounts were calculated at the beginning of the study and entered to the program as calculated amounts. In other words, replacement amounts are included in the amounts represented. Therefore, a proper comparison of the impacts on life cycle stages could not be demonstrated in this study. Yet, as illustrated in Table 4.2, it can be seen that materials' embodied energy got the highest percentage in all impact categories followed by maintenance and replacement when analyzing One Click LCA result distributions by life cycle stages. Table 4.2 again shows that transportation and end of life activities were found to be quite less than the two other life cycle stages. One reason lying behind the less impact observed in transportation is probably LEED v2009 MR Credit 5: Regional Materials. LEED always promotes the use of regional materials in order to diminish the effect of transportation. Hence, the credit requires the use of building materials that have been extracted, harvested, recovered and manufactured within a 500 mile radius of the project site. Although the limit for the credit is to use at least 10% or 20% of the total building materials based on cost, the project mostly used regional materials and/or products in the actual case. Therefore, the effect of transportation did not show an outstanding impact.

One Click LCA and SimaPro are also different from each other in reaching background calculation results. While SimaPro gives detailed calculation information and input & outputs for all processes, One Click LCA only summary of the characterization results where one cannot reach how to get those results by looking at those outputs which makes difficult to get detailed analysis. In other words, practitioner cannot see which characterization factors used during calculation. Moreover, LCA practitioner cannot involve in the development of LCA model passing through all phases as can be done in SimaPro. This is also another trade-off between simplicity and transparency of the programs.

Another difference between the two software is LCA practitioner cannot add or build any product or system in One Click LCA. In other words, practitioner has to use previously defined and recognized product or systems. In contrast, SimaPro allows users to establish new product or systems helping to conduct a comprehensive assessment if a specific product cannot be found in the database (Ghamdi and Bilec, 2016). To illustrate, a rainwater and a greywater treatment system were generated manually in this study in order to fix the real requirements of the project. In other words, practitioner can create any kind of system if the components of the system are known. This property makes SimaPro more flexible than One Click LCA.

4.3.2. Comparison of Baseline and Case Study Building Results

In order to compare the baseline and case study building results in terms of understanding the level of impacts of each impact category, normalization results of both buildings are provided in Figure 4.35. Although inventories of baseline and case study building vary from each other due to the material and system selections, normalization results of both baseline and case study building displayed similar patterns in each impact category. According to World 2000 normalization factors served by SimaPro, ADP-Fossil fuel was estimated to be the most contributing impact category among all others. GWP and AP had very close normalization results followed by EP, POFP and ODP, respectively (Figure 4.35).

As expected, baseline building results was found to be numerically higher than the case study building results in each impact, as expected. This proves that the green and sustainable design approaches and implementations considerably diminish the environmental impacts of a building during its life-time, especially the energy use which is capable of increasing ADP-Fossil fuel results, sharply.

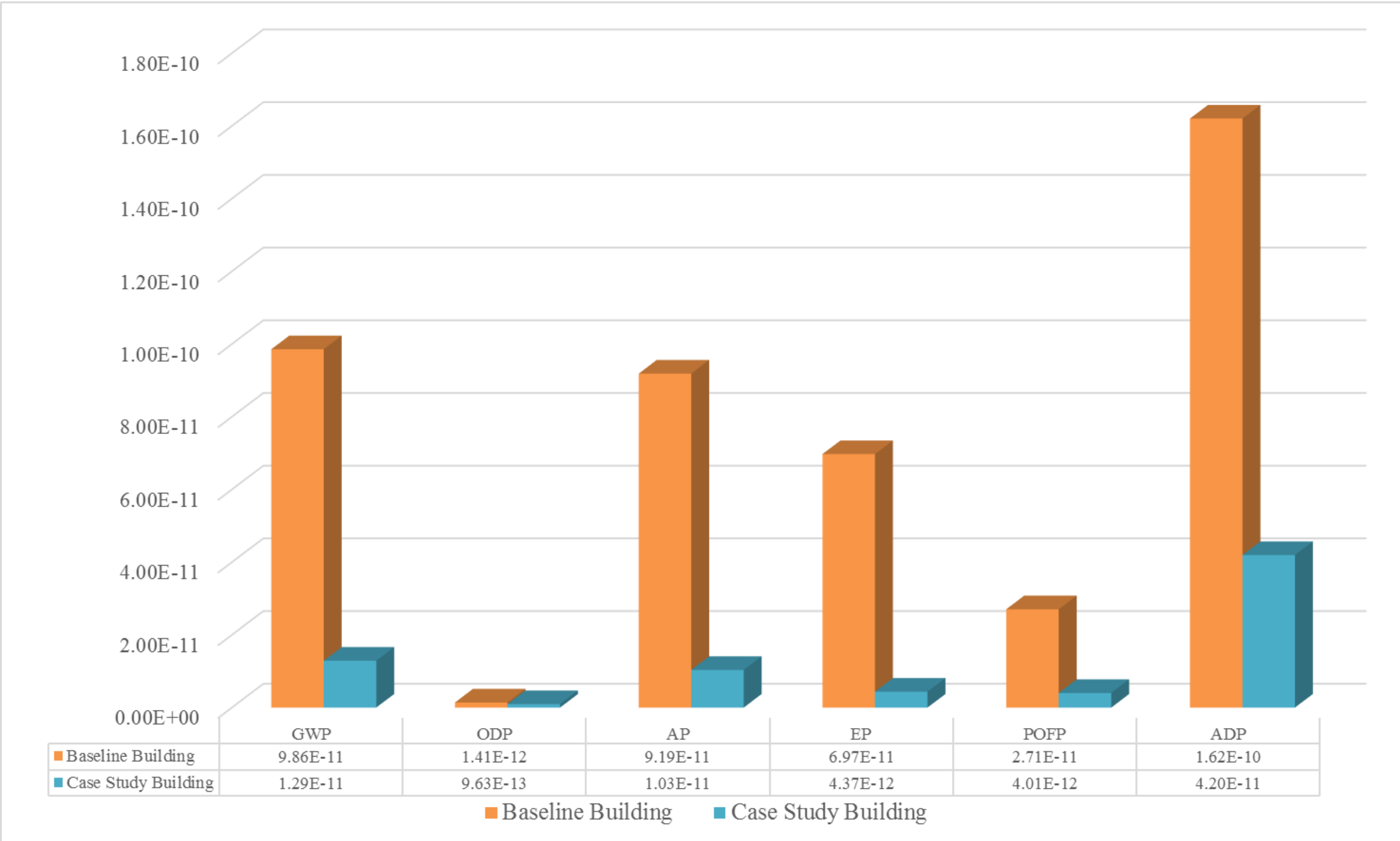

Figure 4.35. Comparison of normalization results baseline and case study building

According to the characterization results, there are a number of materials and/or systems creating numerical difference in characterization results. According to the outputs of SimaPro summarized in Figure 4.22 and Figure 4.30, baseline building results showed greater results in all six impact categories compared to the case study building results, as expected. As shown in these figures, the major difference between baseline and case study building was observed in ADP-Fossil fuel category with the values of 6.16E+04 MJ in the baseline building and 1.77E+04 MJ in the case study building due to the amount of operational energy used during buildings' life cycle. The main reason for the high difference is caused by operational energy use including electricity and natural gas. While the operational energy (natural gas & electricity) consumption of baseline building drew a quite sharp graph in Figure 4.21 with values of 1.55E+04 MJ and 4.26E+04 MJ respectively, the biggest share belonged to only natural gas consumption by 1.33E+04 MJ in case study building since all electricity is met by photovoltaic panels installed in the real building. Therefore, it can be concluded that operational electricity consumption was found to be the most important element in the building's life-cycle. Similarly, when analysing differences in mainly GWP and other impact categories' results of the baseline building as graphically shown in Figure 4.16 to Figure 4.20, it can be seen that the main difference is caused by electricity. A study in Finland reveals that operational energy use including heating and electricity is responsible for almost 80-90% of GWP and AP in a building's life cycle (Aittola et al., 2000). Literature studies also prove this finding. Junnila and Horwath (2003) conducted a study on measuring the impacts of the life cycle stages of an office building. According to the results, electricity use and manufacturing of building materials correspond to the biggest impact among all life cycle stages considered in the study as building material manufacturing, construction process, use of building, maintenance and demolition. Additionally, Scheuer et al. confirms that only HVAC and electricity account for 94.4% of primary energy consumption of 7,300 m^2 six storey building in Michigan. Therefore, study emphasis on the optimization of the operational phase of the building which was found to be responsible for 83% of total environmental burdens.

The other building components posing difference between baseline and case study results are photovoltaic panels, aluminium frame windows and recycling of aluminium and steel in almost all impact categories.

In the baseline and actual case scenarios, photovoltaic panels are only taken into consideration in the actual case posing a significant difference between characterization results. These panels are responsible for the high impacts in all impact categories in the LCA of the case study building in SimaPro (2), as shown in Figure 4.24 to Figure 4.29. In fact, it got the second highest characterization values after natural gas results in all impact categories except EP by having 1.40E+02 kg CO_2 eq in GWP, 2.27E-05 kg CFC-11 eq in ODP, 7.39E-01 kg SO_2 eq in AP, 3.43E-02 kg C_2H_4 eq in POFP and 1.60E+03 MJ in ADP-Fossil fuel. In EP, it has the highest characterization value (2.98E-01 kg PO_4 eq) among all components. The reason for high results in GWP, AP, EP and ADP-Fossil fuel was determined as silicon wafer manufacturing and its upstream processes since silicon crystal growth and casting processes required serious resource consumption and also responsible for emissions. On the other hand, PV cell manufacturing causes increased ODP due to tetrafluoroethylene which has a high ozone-layer depletion potential (Stamford & Azapagic, 2018).

Window frames were also found to be another contributor of the difference in almost all impact categories. While aluminium window frame was chosen as it was installed in the real case, PVC framing was considered in the hypothetical baseline building due to the common use of it in Turkey. As it can be seen from the Figures 4.24 to Figure 4.29, results showed that aluminium window frame was among the most significant elements affecting characterization results in the case study scenario in all impact categories except ODP while PVC did not represent such an impact in the baseline case (Figure 4.16 to Figure 4.21). Asif et al. (2002) conducted a study on the comparison of embodied energies of four types of window frames as aluminium, PVC, Al-clad timber and timber frames with a dimension of 1.2 m x 1.2 m. According to their study, aluminium window frames poses highest environmental burdens due to the hazardous chemicals released and high energy consumption occurred during aluminium production. The results indicated that aluminium window frames consumes 6 GJ while PVC type 2,980 MJ embodied energies. Another study carried by Sinha and Kutnar (2012) revealed quite similar results. In this study, 1 m^2 of window area was assessed in a cradle-to-gate boundary with three different materials as aluminium, PVC and wood. Results showed that aluminium window frame has a GWP of 486 kg CO_2 eq while PVC frame has 258 kg CO_2 eq. This study also proves the negative effect of aluminium frame used in actual building.

Another difference between baseline and case study inventories were the usage of recycled aluminium and steel and their disposal scenarios. In the actual case, building has recycled aluminium in façade cladding and recycled steel used in the structure as shown in Table 3.10. In this case, those materials were sent to recycling in the disposal scenario. On the other hand, aluminium used for the façade and steel used in the building were chosen to be manufactured from raw materials and then sent to landfill without any recycling activity in the baseline case (Table 3.9). In order to find how the usage of these recycled materials affects the results, a trial method was applied. In this trial conducted in SimaPro, reinforcing steel, structural steel and aluminium were first chosen as metals that are produced from scraps and previously used materials. In the second case, these materials were assumed to be manufactured from raw materials. The percentage difference observed are given below:

- For the reinforcing steel, the results decreased by 12.5% in ADP-Fossil fuel, 3.7% in GWP, 10.9% in ODP, 10.7% in POFP, 6.0% in AP and 6.6% in EP
- For structural steel, characterization results displayed decrease by 9.1% in ADP-Fossil fuel, 2.4% in GWP, 7.6% in ODP, 8.9% in POFP, 3.7% in AP and 2.6% in EP.
- For aluminium cladding, following decreases were observed in each impact category: 3.2% in ADP-Fossil fuel, 1.1% in GWP, 0.8% in ODP, 4.2% in POFP, 1.8% in AP and 2.1% in EP.

Literature studies show that recycled aluminum requires almost 95% less energy in production while comparing primary metal production and emits 5% of greenhouse gases. On the other hand, a study on recycling steel indicates that production of steel from steel scrap provides decrease by 73% in kg CO_2 emission and 64% in primary energy as MJ (Boradbend, 2016). As it can be seen from the percentages indicated above, the results did not showed such a great difference in characterization results when aluminium and steel were selected as recycled materials. However, the effects of sending those two materials to the recycling process after demolition significantly affected the results positively, especially the categories of GWP, AP, EP and POFP, as graphically shown in Figures 4.24 to Figure 4.29. Ochsendorf et al. (2011) states that metals having high recycle content like aluminium and steel are often considered to be recycled in the disposal scenario while others are generally sent to the landfill after demolition. Therefore, both metals were treated by recycling in the disposal scenario. A study conducted on a low energy family house in Italy showed that the use of materials that have recycling potential is an effective tool to decrease life cycle impacts (Blengini & Di Carlo, 2010). Renzulli et al (2016) also states that reuse of steel slag provides a large potential for decreasing overall environmental burdens of the steel production. Effect of recycling was mostly seen in POFP by corresponding 46.2% of the total characterization results followed by GWP with 19.1%, AP with 16.4% and EP with 15.4%. It slightly affected ADP-Fossil fuel and ODP with percentages of 6.6% and 2.2%, respectively. The reason of the high benefits in POFP category might be that recycling of steel diminishes the impacts of coking and sintering processes which emit NO_x to the air (Olmez et al., 2016).

Although there are several materials showing difference in the results, there are a number of materials and/or systems having same patterns in common. Natural gas, aluminium cladding, steel and concrete were found to be common and considerably important components in each case.

Literature studies prove that natural gas ranks second following the electricity use during the operation phase (Abd Rashid & Yusoff, 2015). Similarly, although it has the second highest results in each impact category except ODP in baseline case in this study (Figure 4.16 to Figure 4.21), it gets the first place in all impact categories except EP in the case study building results as shown in Figure 4.19 due to the dominant effect of photovoltaic panels on EP results. The impact of natural gas mostly comes from the transportation procedure of the natural gas since it was chosen as imported from Russia. Especially when ODP process contribution results were analysed, it was observed that 1.95E-04 kg CFC-11 eq of total 2.18E-04 kg CFC-11 eq was caused by pipeline transportation of natural gas in actual case. Similar to ODP, GWP and POFP results were also affected by pipeline transportation due to the fact that serious emissions are released such as CO_2, NO_x, CH_4 and its compounds during transportation.

As presented in Figure 4.16 to Figure 4.21 and Figure 4.24 to Figure 4.29, reinforcing and structural steel represented high results in each LCA study. Steel is known to be a material that needs high energy requirements during manufacturing. According to the results, diesel, heat and electricity had the most significant process contributions in steel manufacturing resulting in high GWP. A life cycle assessment on steel production in Italy proves that the most burdening factors in steel production are energy consumption and the toxicity released during processes (Renzulli, et al., 2016). Moreover, hard coal mining quicklime processing used in steel manufacturing, production of pig iron (nitrogen oxides) and sintering processes contributes to the high GWP due to the release of CO_2, CH_4 and nitrogen oxides. These results are also confirmed by the literature study on steel and iron industry in Turkey (Olmez et al., 2016). Similarly, ADP-Fossil fuel results showed hard coal and lignite mine operations increase ADP-Fossil fuel results together with petroleum products and natural gas used during production.

For materials made of aluminium which are aluminium cladding and aluminium window frames are another significant components observed in characterization results. With respect to the literature studies regarding aluminium production, it can be said that the production chain consists of a carbon plant, a reduction plant (smelter), a casting plant and a power plant. Raw alumina is first sent to the reduction plant and then conveyed to the carbon plant to be processes into liquid aluminium using carbon anodes. Then, liquefied aluminium is sent to the casting plant where it turns into primary foundry alloys and extrusion ingots. The power plant serves for the required electricity for all these three plants. Each plant has its own inputs and emissions during the production process. Most significant emissions coming from all plants can be specified as CO_2, CH_4, NO_x, N_2O, SO_2, fluorides, oil, polycyclic aromatic hydrocarbons, dust (PM10), tetrafluoromethane (CF4) and suspended solids which are responsible for GWP (CO_2, CH_4 and N_2O), ODP (CF_4 and NO_x), AP (SO_2 and NO_X), EP (NO_x) and POFP (organics and dust) (Hawari et al., 2014). The production also requires huge amount of energy as 225 MJ/kg (Elshafei & Negm, 2015). This also justifies the results obtained in ADP-Fossil fuel impact category.

Concrete was also determined as a considerable material in all impact categories, as illustrated in Figure 4.16 to Figure 4.21 and Figure 4.24 to Figure 4.29. Despite the fact that embodied energy of concrete is relatively low compared to the other building materials, the amount used in the buildings are high causing high embodied energy results (Asif et al., 2005). The high results are mainly caused by cement production emitting serious amount of CO_2. According to statistics, cement production accounts for 6& - 10% of global CO_2 emission and 12% - 15% of industrial energy use which explains the significant results in GWP and ADP-Fossil fuel (Scrivener et al., 2018). It also utilizes electricity, lubricating oil, diesel and heavy metals resulting in high values in AP, EP and POFP. Natural aggregate can be also considered as an important component leading raise in the results since aggregate production emits CO, NOx, SOx, CH_4, CO_2, N_2O, NMVOC and particulates to the atmosphere (Marinković et al., 2010). This also supports the ODP, AP, EP and POFP result of the study.

4.3.3. Sensitivity Analysis

Due to the nature of the LCA studies, the results are highly dependent on several parameters such as practitioner's experience, choices and assumptions. Therefore, a sensitivity analysis should be conducted in order to understand how the results can change when data selection strategies altered.

As mentioned in Section 3.2.2.2, data selection was done based on two different approaches exist in Ecoinvent 3 throughout the study, which are Attributional and Consequential Methods. Among these, Attributional Method was implemented in the study by considering its specific scope. However, a sensitivity analysis was also performed in order to see the validity of the assumptions. In this sense, case study building was selected as an example. The building was analyzed by using both Attributional and Consequential Methods and the results were compared. Normalized results of both LCAs are shown in Figure 4.36. The results obtained by Attributional Method are represented as “Case Study Building” while the results of Consequential Method are mentioned as “Case Study Building – Modified”.

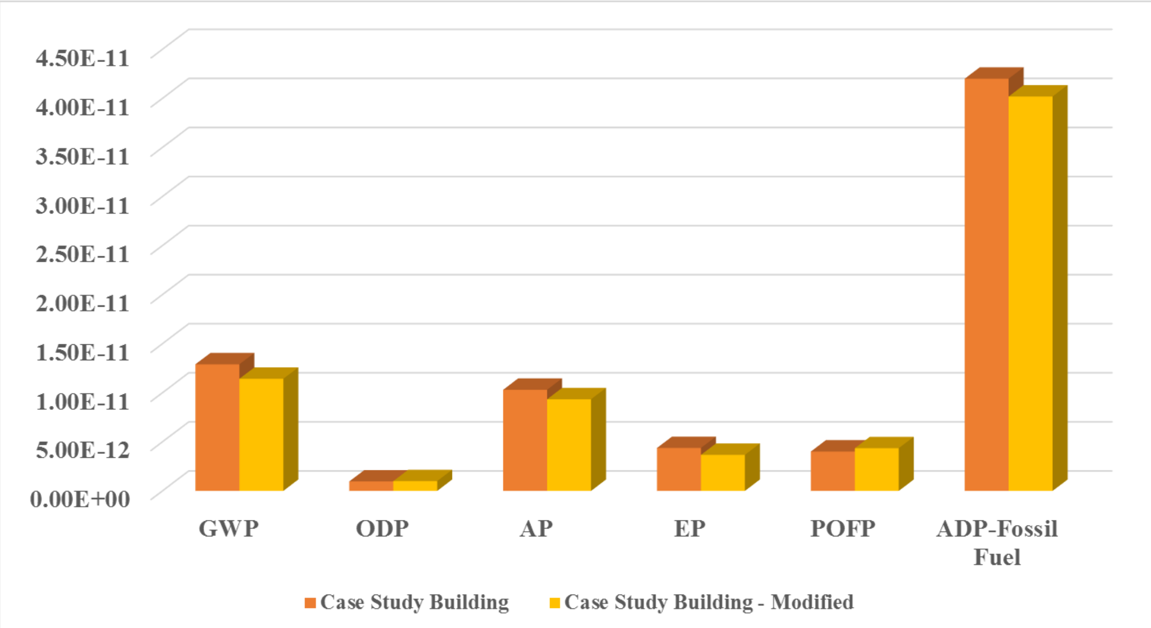

Figure 4.36. Total normalization results of case study building and modified case study building

As it can be seen from Figure 4.36, the results did not affected considerably when data selection strategy was changed. According to characterization results, Case Study Building results found to be higher than Case Study Building – Modified results as 5.8% higher in GWP, 4.3% in AP and %3.8 in EP. On the other hand, Case Study Building – Modified results showed higher percentages as 3.4% in ODP, 4.6% in POFP and 3.7% in ADP-Fossil Fuel. Hence, it can be seen that selection of Attributional or Consequential Methods did not affect study, remarkably.

CHAPTER 5

CONCLUSION

Building industry is responsible for serious environmental problems all over the world. However, new strategies and policies have started to be implemented in recent years in building industry such as green building rating systems, environmental-friendly product design and life cycle assessments for optimum decision making. Yet, the industry still needs to have an integrated, holistic and comprehensive methodology to ensure the maximum benefit from all these sustainability tools.

In this study, one of the goals were identifying discrepancies between LCA tools used in the market. To do this, two LCA programs that can be used for building LCA were assessed. One of the softwares was One Click LCA which was developed especially for building LCA required by green building rating systems while SimaPro was chosen as another LCA tool for this study. Only case study building's LCA was conducted in each softwares. At the end of the study, it was seen that:

- the impact results were not too much different from each other and obtained as comparable results. The differences may be caused by several reasons like slight difference in system boundaries, data availability and data selection in each program. The top lists of most contributing elements were slightly different from each other.
- Although the results were close to each other, representation styles of each program were highly different. One Click LCA demonstrates results via percentage graphs and a detailed excel format. Moreover, it does not give normalization results which may be considered as a lack in an academic study. However, since the purpose of the program which is to allow designers, architects, engineers, etc. to conduct LCA for mostly commercial purposes, it can be concluded that it is more suitable for the requirements of green building

rating systems. It is also quicker, user-friendly, customer-supportive and open to update.

- On the other hand, SimaPro is more proper for an academic study due to its higher database and detailed calculation procedure. Therefore, the study showed that although all LCA tools are effective in measuring environmental impacts of a product, the aim and content of the LCA should determine the program to be used by considering the level of transparency.

The study also tried to figure out the integration of life cycle assessment and a widely used green building rating system called LEED. Accordingly, a certified green building located in Turkey was chosen as a case study building in order to be assessed in terms of environmental burdens by using LCA approach. Then, the building was compared to a hypothetical baseline building having same floor area, orientation and location. The results showed that:

- implementing renewable energy sources like photovoltaic panels provides the highest benefit during the life cycle of the building since it eliminates the use of market electricity in considerable amounts.
- When the dramatic effect of operational energy is considered, it gets the highest importance in the comparison of baseline and actual cases.
- Beside electricity, natural gas was also found to be another significant component affecting all impact categories. Amount of natural gas used in the actual case is lower than the baseline case with the help of good insulation and better glazing resulting in lower impacts compared to the baseline case.
- Additionally, aluminum vs PVC window frames and disposal scenarios created difference in results.
- While the results in actual case were higher due to the use of aluminum frames, PVC did not showed substantial impact on any impact category.
- Disposal scenarios were also slightly different from each other resulting significant variations. Sending aluminium and steel to the recycling affected the case study building results quite positively while all demolition waste was

sent to landfill in baseline case causing higher environmental burdens. Hence, the importance of recyclable materials and recycling activities were again seen in a quantitative way.

- Another finding is that the most contributing elements were almost the same in both LCAs. Aluminum cladding, steel and concrete had the highest shares after operational energy use and should be considered in detailed during the design period of the buildings.

Lastly, sensitivity analysis conducted to see the accuracy of data selection method was showed that data selection method did not alter the results more than 6%.

CHAPTER 6

RECOMMENDATION

Although Life Cycle Assessment is a tool that enables practitioners to give quantitative and comparable results, it is highly dependent on data availability and assumptions. When we consider the current studies and databases in Turkey, we can conclude that existing generic and EPD data is not sufficient enough to conduct a fully accurate LCA especially on building industry. Even if there are recent attempts to generate a national LCA database, it is still an ongoing procedure and needs to be enhanced in coming years. In this way, assumptions can be limited in any study leading a more accurate and trustable decision making in building industry.

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APPENDICES

A. Characterization Results of the Case Study Building in One Click LCA

Table A1. *Characterization results of the case study building in One Click LCA*

Impact Category	Floor standing gas boiler, French average, P=25kW	Circulator pump	Water chiller, HVAC, French average, 100 kW	Circulation pump, < 50 W	Flat collector, solar	Bathroom mixer faucet	Porcelain WC kit
ADP (MJ)	5.19E+00	2.00E-01	2.02E+01	4.50E+00	1.88E+01	2.18E+00	3.20E+01
GWP (kg CO_2)	3.55E-01	1.48E-02	1.42E+00	3.35E-01	1.37E+00	1.54E-01	2.00E+00
ODP (kg CFC-11)	1.98E-08	1.28E-12	1.25E-07	3.05E-11	4.12E-10	3.38E-11	2.67E-07
POFP (kg C_2H_4)	2.01E-04	5.05E-06	7.52E-04	1.14E-04	5.54E-04	9.85E-05	8.09E-04
AP (kg SO_2)	2.02E-03	6.86E-05	9.95E-03	1.55E-03	1.06E-02	1.84E-03	1.32E-02
EP (kg PO_4)	1.98E-04	5.59E-06	2.48E-03	1.26E-04	4.64E-04	7.20E-05	1.97E-03

Table A1. *Characterization results of the case study building in One Click LCA - continued*

Impact Category	**Stormwater storage tank**	**Solar panel photovoltaic system, EU average**	**Ceramic façade cladding, 67.07 kg/m2, 2050 - 2200 kg/m3**	**Aluminum composite panel**	**Rock wool insulation, in slabs, L = 0.034 W/mK (034), 0.035 W/mK (035)**	**Gypsum plaster board, 12.5 mm, 10.6 kg/m2, 848 kg/m3**	**Water based textured paint,1.28 kg/l**
ADP (MJ)	1.08E+02	1.39E+03	1.90E+02	3.97E+02	1.80E+01	2.03E+01	2.23E+00
GWP (kg CO_2)	5.55E+00	9.25E+01	1.26E+01	3.62E+01	8.91E-01	1.19E+00	1.34E-01
ODP (kg CFC-11)	3.31E-07	2.18E-05	9.52E-09	1.11E-06	7.48E-10	3.81E-08	1.34E-08
POFP (kg C_2H_4)	1.22E-03	1.08E-02	2.11E-03	4.93E-02	4.00E-04	3.44E-04	7.14E-05
AP (kg SO_2)	1.83E-02	5.45E-01	2.85E-02	1.29E-02	7.56E-03	4.20E-03	8.44E-04
EP (kg PO_4)	2.96E-03	2.68E-01	2.50E-03	2.13E-01	1.21E-03	6.60E-04	2.14E-04

Table A1. *Characterization results of the case study building in One Click LCA - continued*

Impact Category	**Two component solvent free epoxy coating, 1.496-1.604 kg/l**	**Waterborne acrylic thin film intumescent coating, 1.4 kg/l**	**Acrylic polyurethane coating, 1.5 kg/l, 73% solids/volume**	**Two component epoxy coating, 1.6 kg/l, 74% solids/volume, film thickness**	**Two component epoxy coating, 1.6 kg/l, 74% solids/volume, film thickness**	**Waterborne epoxy coating, for carbon steel and galvanized steel, 2.5 kg/l,**	**Cement-polymer emulsion mortar, 1350 kg/m3**
ADP (MJ)	4.79E+00	3.51E+00	5.44E+00	2.50E-04	7.24E+00	1.60E+01	4.17E+00
GWP (kg CO_2)	3.14E-01	2.21E-01	2.84E-01	3.89E-01	3.95E-01	1.37E+00	3.43E-01
ODP (kg CFC-11)	2.40E-09	1.92E-08	7.13E-08	3.10E-09	3.03E-09	8.91E-09	1.90E-08
POFP (kg C_2H_4)	2.01E-04	9.66E-05	2.21E-04	2.50E-04	2.47E-04	6.47E-04	4.24E-04
AP (kg SO_2)	1.42E-03	1.66E-03	1.69E-03	1.78E-03	1.96E-03	1.30E-02	1.04E-04
EP (kg PO_4)	3.45E-04	6.53E-04	3.41E-04	4.13E-04	4.25E-04	3.87E-03	1.09E-03

Table A1. *Characterization results of the case study building in One Click LCA - continued*

Impact Category	**Multi-layer parquet flooring, 14 mm, 9.52 kg/m2**	**Glue laminated wood beam, pine, 540 kg/m3**	**PVC based, multi-layer, synthetic waterproofing roof sheet, non-woven glass inlay, 1.2 mm**	**Granite interior flooring, tiles, 2x40x60 cm, installed with 4 cm adhesive mortar layer**	**Tufted carpet tiles, 4.718 kg/m2**	**Resilient polyurethane floor covering, 2.5 mm, 3.75 kg/m2**	**Ready mix concrete, excluding rebar, C35/45 (B35 M40)**
ADP (MJ)	2.74E+01	5.78E-01	1.71E+01	6.64E+02	1.29E+02	1.22E+02	3.76E+02
GWP (kg CO_2)	3.19E-02	5.20E-02	1.49E+00	4.73E+00	8.82E+00	4.30E+00	5.74E+01
ODP (kg CFC-11)	5.96E-10	4.73E-09	1.49E-09	3.05E-07	1.45E-08	8.73E-08	1.69E-06
POFP (kg C_2H_4)	1.14E-03	2.01E-05	9.01E-04	2.51E-03	2.93E-03	7.16E-03	1.43E-01
AP (kg SO_2)	1.58E-02	3.27E-02	7.63E-03	3.33E-02	1.57E-02	2.91E-02	6.14E-02
EP (kg PO_4)	1.51E-03	8.53E-03	3.21E-04	9.17E-03	2.58E-03	5.83E-03	1.05E-02

Table A1. *Characterization results of the case study building in One Click LCA - continued*

Impact Category	**Autoclaved aerated concrete blocks, thicknesses: 5, 7.5, 9, 10, 15, 20, 25, 30, 35, 40 cm (AKG Gazbeton)**	**Profiled steel sheeting, hot-dip galvanized (Ruukki)**	**Ribbed steel rebar mesh, stainless, 21% zinc, 79% recycled steel (Rhein Habaz)**	**Structural steel profiles, generic, 0% recycled content (only virgin materials), I, H, U, L, and T sections**	**Carbon steel reinforcing bar (secondary production route – scrap), 98.3% recycled content (Izmir Demir Celik Sanayi)**	**Aluminium window system, triple glazed, 1230 x 1480 mm, 72.96 kg, 40.1 kg/m2, AWS 75.SI+ (Schüco)**
ADP (MJ)	4.75E+01	1.35E+02	3.50E+01	3.21E+03	3.15E+02	8.47E+02
GWP (kg CO2)	6.05E+00	1.76E+01	2.62E+00	2.24E+02	2.48E+01	6.16E+01
ODP (kg CFC-11)	3.24E-07	9.62E-08	1.12E-07	1.09E-05	3.92E-08	1.38E-06
POFP (kg C2H4)	3.29E-03	4.05E-03	8.66E-04	7.98E-02	8.23E-03	2.19E-02
AP (kg SO2)	1.31E-02	4.30E-02	1.25E-02	1.19E+00	1.16E-01	2.12E-01
EP (kg PO4)	3.10E-03	4.50E-03	1.37E-03	1.15E-01	1.11E-02	2.68E-02

B. Characterization and Normalization Results of the Case Study Building in SimaPro (1)

Table B1. *Characterization results of the case study building in SimaPro (1)*

<table>
<tr><th>Impact Category</th><th>Concrete, 35MPa {GLO}| market for | Alloc Rec, U</th><th>Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S</th><th>Reinforcing steel {GLO}| market for | Alloc Def, U</th><th>Galvanized steel sheet, at plant/RNA</th><th>Autoclaved aerated concrete block {GLO}| market for | Alloc Rec, U</th><th>Steel, low-alloyed {GLO}| market for | Alloc Def, U</th><th>Cladding, crossbar-pole, aluminium {GLO}| market for | Alloc Def, U</th><th>Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m3 RER S</th></tr>
<tr><td>ADP (MJ)</td><td>5.63E+02</td><td>1.65E+01</td><td>5.49E+02</td><td>1.75E+02</td><td>3.59E+01</td><td>6.40E+02</td><td>7.01E+02</td><td>2.27E+01</td></tr>
<tr><td>GWP (kg CO_2)</td><td>9.52E+01</td><td>1.59E+00</td><td>5.67E+01</td><td>1.72E+01</td><td>5.79E+00</td><td>6.49E+01</td><td>6.59E+01</td><td>2.08E+00</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>4.70E-06</td><td>0.00E+00</td><td>3.02E-06</td><td>4.75E-08</td><td>2.78E-07</td><td>3.34E-06</td><td>4.88E-06</td><td>1.06E-07</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>9.07E-03</td><td>7.22E-04</td><td>3.22E-02</td><td>5.28E-03</td><td>7.49E-04</td><td>3.41E-02</td><td>2.57E-02</td><td>6.51E-04</td></tr>
<tr><td>AP (kg SO_2)</td><td>2.12E-01</td><td>4.88E-03</td><td>2.43E-01</td><td>3.35E-02</td><td>1.36E-02</td><td>3.08E-01</td><td>3.83E-01</td><td>1.52E-02</td></tr>
<tr><td>EP (kg PO_4)</td><td>6.03E-02</td><td>3.37E-04</td><td>1.18E-01</td><td>-2.00E-02</td><td>3.31E-03</td><td>2.18E-01</td><td>1.06E-01</td><td>1.57E-03</td></tr>
</table>

Table B1. *Characterization results of the case study building in SimaPro (1) - continued*

<table>
<tr><th>Impact Category</th><th>Gypsum plasterboard {GLO}| market for | Alloc Rec, U</th><th>Ceramic tile {GLO}| market for | Alloc Rec, U</th><th>Single-ply, white, polyester reinforced PVC roofing membrane, 48 mils (1.219 mm)/m2/RNA</th><th>Natural stone plate, polished {GLO}| market for | Alloc Rec, U</th><th>Prefinished engineered wood flooring, at engineered wood flooring plant, E/m3/RNA</th><th>Glued laminated timber, for indoor use {GLO}| market for | Alloc Rec, U</th><th>Window frame, aluminium, U=1.6 W/m2K {GLO}| market for | Alloc Rec, U</th><th>Glazing, triple, U<0.5 W/m2K {GLO}| market for | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>1.84E+01</td><td>8.10E+01</td><td>2.04E+01</td><td>8.87E+01</td><td>1.48E+01</td><td>5.87E-01</td><td>5.97E+02</td><td>1.89E+02</td></tr>
<tr><td>GWP (kg CO_2)</td><td>1.74E+00</td><td>6.26E+00</td><td>9.36E-01</td><td>7.52E+00</td><td>1.04E+00</td><td>4.15E-02</td><td>6.16E+01</td><td>1.68E+01</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>8.96E-08</td><td>5.32E-07</td><td>7.78E-08</td><td>5.62E-07</td><td>9.73E-08</td><td>5.36E-09</td><td>2.22E-06</td><td>1.27E-06</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>4.93E-04</td><td>1.96E-03</td><td>5.96E-04</td><td>1.50E-03</td><td>1.05E-03</td><td>2.45E-05</td><td>2.19E-02</td><td>4.96E-03</td></tr>
<tr><td>AP (kg SO_2)</td><td>1.11E-02</td><td>3.30E-02</td><td>9.80E-03</td><td>4.12E-02</td><td>9.28E-03</td><td>2.53E-04</td><td>3.53E-01</td><td>1.23E-01</td></tr>
<tr><td>EP (kg PO_4)</td><td>2.40E-03</td><td>8.90E-03</td><td>6.70E-03</td><td>1.39E-02</td><td>5.76E-04</td><td>7.86E-05</td><td>8.38E-02</td><td>2.22E-02</td></tr>
</table>

Table B1. *Characterization results of the case study building in SimaPro (1) - continued*

<table>
<tr><th>Impact Category</th><th>Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, U</th><th>Coating powder {GLO}| market for | Alloc Rec, U</th><th>Acrylic filler {GLO}| market for | Alloc Rec, U</th><th>Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Alloc Rec, U</th><th>Cement mortar {CH}| market for cement mortar | Alloc Rec, U</th><th>Gas boiler {GLO}| market for | Alloc Rec, U</th><th>Flat plate solar collector, Cu absorber {GLO}| market for | Alloc Rec, U</th><th>Photovoltaic panel, single-Si wafer {GLO}| market for | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>1.10E+00</td><td>1.55E+01</td><td>3.14E-01</td><td>1.32E+00</td><td>6.30E-01</td><td>1.50E+00</td><td>1.45E+01</td><td>1.60E+03</td></tr>
<tr><td>GWP (kg CO_2)</td><td>7.23E-02</td><td>1.13E+00</td><td>1.60E-02</td><td>1.22E-01</td><td>1.43E-01</td><td>1.40E-01</td><td>1.42E+00</td><td>1.40E+02</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>6.48E-09</td><td>7.02E-08</td><td>1.63E-09</td><td>1.01E-08</td><td>5.89E-09</td><td>7.65E-09</td><td>8.32E-08</td><td>2.27E-05</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>4.50E-05</td><td>1.09E-03</td><td>8.57E-06</td><td>7.45E-05</td><td>1.94E-05</td><td>8.11E-05</td><td>9.18E-04</td><td>3.43E-02</td></tr>
<tr><td>AP (kg SO_2)</td><td>5.50E-04</td><td>7.07E-03</td><td>9.73E-05</td><td>8.48E-04</td><td>3.52E-04</td><td>1.30E-03</td><td>1.95E-02</td><td>7.39E-01</td></tr>
<tr><td>EP (kg PO_4)</td><td>1.25E-04</td><td>1.77E-03</td><td>2.11E-05</td><td>2.48E-04</td><td>9.00E-05</td><td>7.54E-04</td><td>9.83E-03</td><td>2.98E-01</td></tr>
</table>

Table B1. *Characterization results of the case study building in SimaPro (1) - continued*

<table>
<tr><th>Impact Category</th><th>Pump, 40W {GLO}| market for | Alloc Rec, U</th><th>Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {GLO}| market for | Alloc Rec, U</th><th>Absorption chiller, 100kW {GLO}| market for | Alloc Rec, U</th><th>Rainwater system</th><th>Greywater system</th><th>Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Rec, U</th><th>Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Rec, U</th><th>Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>1.81E+00</td><td>7.41E+01</td><td>2.94E+01</td><td>6.76E-03</td><td>1.52E-02</td><td>2.68E+01</td><td>9.33E+00</td><td>3.98E+01</td></tr>
<tr><td>GWP (kg CO_2)</td><td>1.69E-01</td><td>7.24E+00</td><td>2.77E+00</td><td>9.20E-04</td><td>1.49E-03</td><td>1.58E+00</td><td>6.03E-01</td><td>2.48E+00</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>8.90E-09</td><td>3.39E-07</td><td>1.51E-07</td><td>4.50E-11</td><td>7.65E-11</td><td>3.20E-07</td><td>1.13E-07</td><td>4.86E-07</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>1.37E-04</td><td>2.41E-03</td><td>1.91E-03</td><td>1.20E-07</td><td>9.20E-07</td><td>2.13E-04</td><td>6.99E-05</td><td>3.71E-04</td></tr>
<tr><td>AP (kg SO_2)</td><td>2.66E-03</td><td>4.21E-02</td><td>3.37E-02</td><td>2.61E-06</td><td>6.16E-06</td><td>3.59E-03</td><td>1.11E-03</td><td>1.04E-02</td></tr>
<tr><td>EP (kg PO_4)</td><td>1.56E-03</td><td>1.13E-02</td><td>1.98E-02</td><td>7.35E-07</td><td>2.39E-06</td><td>5.89E-04</td><td>1.57E-04</td><td>2.15E-03</td></tr>
</table>

Table B2. *Normalization results of the case study building in SimaPro (1)*

Impact Category	**Concrete, 35MPa {GLO}| market for | Alloc Rec, U**	**Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S**	**Reinforcing steel {GLO}| market for | Alloc Def, U**	**Galvanized steel sheet, at plant/RNA**	**Autoclaved aerated concrete block {GLO}| market for | Alloc Rec, U**	**Steel, low-alloyed {GLO}| market for | Alloc Def, U**	**Cladding, crossbar-pole, aluminium {GLO}| market for | Alloc Def, U**	**Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m3 RER S**
ADP-FF	1.48E-12	4.33E-14	1.44E-12	4.61E-13	9.43E-14	1.68E-12	1.84E-12	5.97E-14
GWP	2.27E-12	3.81E-14	1.35E-12	4.11E-13	1.38E-13	1.55E-12	1.58E-12	4.97E-14
ODP	2.07E-14	0.00E+00	1.33E-14	2.09E-16	1.23E-15	1.47E-14	2.15E-14	4.66E-16
POFP	2.47E-13	1.96E-14	8.77E-13	1.44E-13	2.04E-14	9.29E-13	6.99E-13	1.77E-14
AP	8.87E-13	2.05E-14	1.02E-12	1.40E-13	5.70E-14	1.29E-12	1.60E-12	6.38E-14
EP	3.81E-13	2.13E-15	7.49E-13	-1.26E-13	2.09E-14	1.38E-12	6.70E-13	9.90E-15

Table B2. *Normalization results of the case study building in SimaPro (1) - continued*

<table>
<tr><th>Impact Category</th><th>Gypsum plasterboard {GLO}| market for | Alloc Rec, U</th><th>Ceramic tile {GLO}| market for | Alloc Rec, U</th><th>Single-ply, white, polyester reinforced PVC roofing membrane, 48 mils (1.219 mm)/m2/RNA</th><th>Natural stone plate, polished {GLO}| market for | Alloc Rec, U</th><th>Prefinished engineered wood flooring, at engineered wood flooring plant, E/m3/RNA</th><th>Glued laminated timber, for indoor use {GLO}| market for | Alloc Rec, U</th><th>Window frame, aluminium, U=1.6 W/m2K {GLO}| market for | Alloc Rec, U</th><th>Glazing, triple, U<0.5 W/m2K {GLO}| market for | Alloc Rec, U</th></tr>
<tr><td>ADP-FF</td><td>4.85E-14</td><td>2.13E-13</td><td>5.36E-14</td><td>2.33E-13</td><td>3.90E-14</td><td>1.54E-15</td><td>1.57E-12</td><td>4.96E-13</td></tr>
<tr><td>GWP</td><td>4.17E-14</td><td>1.50E-13</td><td>2.24E-14</td><td>1.80E-13</td><td>2.49E-14</td><td>9.91E-16</td><td>1.47E-12</td><td>4.03E-13</td></tr>
<tr><td>ODP</td><td>3.95E-16</td><td>2.35E-15</td><td>3.43E-16</td><td>2.48E-15</td><td>4.29E-16</td><td>2.37E-17</td><td>9.80E-15</td><td>5.61E-15</td></tr>
<tr><td>POFP</td><td>1.34E-14</td><td>5.34E-14</td><td>1.62E-14</td><td>4.08E-14</td><td>2.85E-14</td><td>6.66E-16</td><td>5.95E-13</td><td>1.35E-13</td></tr>
<tr><td>AP</td><td>4.66E-14</td><td>1.38E-13</td><td>4.11E-14</td><td>1.73E-13</td><td>3.89E-14</td><td>1.06E-15</td><td>1.48E-12</td><td>5.15E-13</td></tr>
<tr><td>EP</td><td>1.52E-14</td><td>5.62E-14</td><td>4.23E-14</td><td>8.76E-14</td><td>3.64E-15</td><td>4.97E-16</td><td>5.29E-13</td><td>1.40E-13</td></tr>
</table>

Table B2. *Normalization results of the case study building in SimaPro (1) - continued*

Impact Category	**Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, U**	**Coating powder {GLO}| market for | Alloc Rec, U**	**Acrylic filler {GLO}| market for | Alloc Rec, U**	**Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Alloc Rec, U**	**Cement mortar {CH}| market for cement mortar | Alloc Rec, U**	**Gas boiler {GLO}| market for | Alloc Rec, U**	**Flat plate solar collector, Cu absorber {GLO}| market for | Alloc Rec, U**	**Photovoltaic panel, single-Si wafer {GLO}| market for | Alloc Rec, U**
ADP-FF	2.88E-15	4.07E-14	8.26E-16	3.48E-15	1.66E-15	3.95E-15	3.82E-14	4.22E-12
GWP	1.73E-15	2.70E-14	3.83E-16	2.93E-15	3.42E-15	3.34E-15	3.40E-14	3.35E-12
ODP	2.86E-17	3.10E-16	7.18E-18	4.44E-17	2.60E-17	3.37E-17	3.67E-16	1.00E-13
POFP	1.22E-15	2.95E-14	2.33E-16	2.03E-15	5.29E-16	2.21E-15	2.50E-14	9.32E-13
AP	2.30E-15	2.96E-14	4.08E-16	3.55E-15	1.48E-15	5.46E-15	8.17E-14	3.10E-12
EP	7.93E-16	1.12E-14	1.33E-16	1.57E-15	5.69E-16	4.76E-15	6.21E-14	1.88E-12

Table B2. *Normalization results of the case study building in SimaPro (1) - continued*

Impact Category	**Pump, 40W {GLO}| market for | Alloc Rec, U**	**Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {GLO}| market for | Alloc Rec, U**	**Absorption chiller, 100kW {GLO}| market for | Alloc Rec, U**	**Rainwater system**	**Greywater system**	**Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Rec, U**	**Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Rec, U**	**Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Alloc Rec, U**
ADP-FF	4.76E-15	1.95E-13	7.72E-14	1.78E-17	3.98E-17	7.04E-14	2.45E-14	2.19E-12
GWP	4.04E-15	1.73E-13	6.63E-14	2.20E-17	3.56E-17	3.77E-14	1.44E-14	1.24E-12
ODP	3.93E-17	1.50E-15	6.67E-16	1.99E-19	3.37E-19	1.41E-15	4.98E-16	4.48E-14
POFP	3.72E-15	6.55E-14	5.21E-14	3.27E-18	2.50E-17	5.80E-15	1.90E-15	2.11E-13
AP	1.11E-14	1.77E-13	1.41E-13	1.09E-17	2.58E-17	1.51E-14	4.66E-15	9.07E-13
EP	9.89E-15	7.16E-14	1.25E-13	4.64E-18	1.51E-17	3.72E-15	9.94E-16	2.83E-13

C. Characterization and Normalization Results of the Baseline Building in SimaPro

Table C1. *Characterization results of the baseline building in SimaPro*

Impact Category	**Concrete, 35MPa {GLO}| market for | Alloc Rec, U**	**Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S**	**Reinforcing steel {GLO}| market for | Alloc Rec, U**	**Galvanized steel sheet, at plant/RNA**	**Autoclaved aerated concrete block {GLO}| market for | Alloc Rec, U**	**Steel, low-alloyed {GLO}| market for | Alloc Rec, U**
ADP-(MJ)	5.63E+02	1.65E+01	6.27E+02	1.75E+02	3.59E+01	7.05E+02
GWP (kg CO_2)	9.52E+01	1.59E+00	5.89E+01	1.72E+01	5.79E+00	6.66E+01
ODP (kg CFC-11)	4.70E-06	0.00E+00	3.39E-06	4.75E-08	2.78E-07	3.62E-06
POFP (kg C_2H_4)	9.07E-03	7.22E-04	3.61E-02	5.28E-03	7.49E-04	3.75E-02
AP (kg SO_2)	2.12E-01	4.88E-03	2.59E-01	3.35E-02	1.36E-02	3.20E-01
EP (kg PO_4)	6.03E-02	3.37E-04	1.27E-01	-2.00E-02	3.31E-03	2.24E-01

Table C1. *Characterization results of the baseline building in SimaPro - continued*

Impact Category	**Cladding, crossbar-pole, aluminium {GLO}| market for | Alloc Rec, U**	**Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m3 RER S**	**Gypsum plasterboard {GLO}| market for | Alloc Rec, U**	**Ceramic tile {GLO}| market for | Alloc Rec, U**	**Single-ply, white, polyester reinforced PVC roofing membrane, 48 mils (1.219 mm)/m2/RNA**	**Natural stone plate, polished {GLO}| market for | Alloc Rec, U**
ADP (MJ)	7.24E+02	2.27E+01	1.84E+01	8.10E+01	2.04E+01	8.87E+01
GWP (kg CO_2)	6.67E+01	2.08E+00	1.74E+00	6.26E+00	9.36E-01	7.52E+00
ODP (kg CFC-11)	4.92E-06	1.06E-07	8.96E-08	5.32E-07	7.78E-08	5.62E-07
POFP (kg C_2H_4)	2.69E-02	6.51E-04	4.93E-04	1.96E-03	5.96E-04	1.50E-03
AP (kg SO_2)	3.87E-01	1.52E-02	1.11E-02	3.30E-02	9.80E-03	4.12E-02
EP (kg PO_4)	1.08E-01	1.57E-03	2.40E-03	8.90E-03	6.70E-03	1.39E-02

Table C1. *Characterization results of the baseline building in SimaPro - continued*

Impact Category	**Prefinished engineered wood flooring, at engineered wood flooring plant, E/m3/RNA**	**Glued laminated timber, for indoor use {GLO}| market for | Alloc Rec, U**	**Window frame, poly vinyl chloride, U=1.6 W/m2K {GLO}| market for | Alloc Rec, U**	**Glazing, double, U<1.1 W/m2K {GLO}| market for | Alloc Rec, U**	**Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, U**	**Coating powder {GLO}| market for | Alloc Rec, U**
ADP (MJ)	1.48E+01	5.87E-01	3.16E+02	1.14E+02	1.10E+00	1.55E+01
GWP (kg CO_2)	1.04E+00	4.15E-02	1.88E+01	9.98E+00	7.23E-02	1.13E+00
ODP (kg CFC-11)	9.73E-08	5.36E-09	7.11E-07	1.09E-06	6.48E-09	7.02E-08
POFP (kg C_2H_4)	1.05E-03	2.45E-05	5.39E-03	3.09E-03	4.50E-05	1.09E-03
AP (kg SO_2)	9.28E-03	2.53E-04	1.05E-01	7.65E-02	5.50E-04	7.07E-03
EP (kg PO_4)	5.76E-04	7.86E-05	3.39E-02	1.27E-02	1.25E-04	1.77E-03

Table C1. *Characterization results of the baseline building in SimaPro - continued*

<table>
<tr><th>Impact Category</th><th>Acrylic filler {GLO}| market for | Alloc Rec, U</th><th>Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Alloc Rec, U</th><th>Cement mortar {CH}| market for cement mortar | Alloc Rec, U</th><th>Gas boiler {GLO}| market for | Alloc Rec, U</th><th>Pump, 40W {GLO}| market for | Alloc Rec, U</th><th>Tap water {RER}| market group for | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>3.14E-01</td><td>1.32E+00</td><td>6.30E-01</td><td>1.50E+00</td><td>1.81E+00</td><td>1.45E-03</td></tr>
<tr><td>GWP (kg CO_2)</td><td>1.60E-02</td><td>1.22E-01</td><td>1.43E-01</td><td>1.40E-01</td><td>1.69E-01</td><td>1.26E-04</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>1.63E-09</td><td>1.01E-08</td><td>5.89E-09</td><td>7.65E-09</td><td>8.90E-09</td><td>1.33E-11</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>8.57E-06</td><td>7.45E-05</td><td>1.94E-05</td><td>8.11E-05</td><td>1.37E-04</td><td>2.81E-08</td></tr>
<tr><td>AP (kg SO_2)</td><td>9.73E-05</td><td>8.48E-04</td><td>3.52E-04</td><td>1.30E-03</td><td>2.66E-03</td><td>6.32E-07</td></tr>
<tr><td>EP (kg PO_4)</td><td>2.11E-05</td><td>2.48E-04</td><td>9.00E-05</td><td>7.54E-04</td><td>1.56E-03</td><td>3.42E-07</td></tr>
</table>

Table C1. *Characterization results of the baseline building in SimaPro - continued*

Impact Category	Natural gas, high pressure {GR}| import from RU | Alloc Rec, U	Electricity, low voltage {TR}| market for | Alloc Rec, U	Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Rec, U	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Rec, U	Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Alloc Rec, U
ADP (MJ)	1.55E+04	4.26E+04	2.68E+01	6.81E+00	3.31E+01
GWP (kg CO_2)	3.01E+02	3.46E+03	1.58E+00	4.40E-01	2.07E+00
ODP (kg CFC-11)	2.34E-04	6.39E-05	3.20E-07	8.24E-08	4.04E-07
POFP (kg C_2H_4)	1.06E-01	7.56E-01	2.13E-04	5.10E-05	3.09E-04
AP (kg SO_2)	1.39E+00	1.90E+01	3.59E-03	8.12E-04	8.63E-03
EP (kg PO_4)	2.54E-01	1.02E+01	5.89E-04	1.15E-04	1.79E-03

Table C2. *Normalization results of the baseline building in SimaPro*

Impact Category	**Concrete, 35MPa {GLO}| market for | Alloc Rec, U**	**Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S**	**Reinforcing steel {GLO}| market for | Alloc Rec, U**	**Galvanized steel sheet, at plant/RNA**	**Autoclaved aerated concrete block {GLO}| market for | Alloc Rec, U**	**Steel, low-alloyed {GLO}| market for | Alloc Rec, U**
ADP-FF	1.48E-12	4.33E-14	1.65E-12	4.61E-13	9.43E-14	1.85E-12
GWP	2.27E-12	3.81E-14	1.41E-12	4.11E-13	1.38E-13	1.59E-12
ODP	2.07E-14	0.00E+00	1.50E-14	2.09E-16	1.23E-15	1.59E-14
POFP	2.47E-13	1.96E-14	9.83E-13	1.44E-13	2.04E-14	1.02E-12
AP	8.87E-13	2.05E-14	1.08E-12	1.40E-13	5.70E-14	1.34E-12
EP	3.81E-13	2.13E-15	8.02E-13	-1.26E-13	2.09E-14	1.42E-12

Table C2. *Normalization results of the baseline building in SimaPro - continued*

Impact Category	**Cladding, crossbar-pole, aluminium {GLO}| market for | Alloc Rec, U**	**Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m3 RER S**	**Gypsum plasterboard {GLO}| market for | Alloc Rec, U**	**Ceramic tile {GLO}| market for | Alloc Rec, U**	**Single-ply, white, polyester reinforced PVC roofing membrane, 48 mils (1.219 mm)/m2/RNA**	**Natural stone plate, polished {GLO}| market for | Alloc Rec, U**
ADP-FF	1.90E-12	5.97E-14	4.85E-14	2.13E-13	5.36E-14	2.33E-13
GWP	1.59E-12	4.97E-14	4.17E-14	1.50E-13	2.24E-14	1.80E-13
ODP	2.17E-14	4.66E-16	3.95E-16	2.35E-15	3.43E-16	2.48E-15
POFP	7.30E-13	1.77E-14	1.34E-14	5.34E-14	1.62E-14	4.08E-14
AP	1.62E-12	6.38E-14	4.66E-14	1.38E-13	4.11E-14	1.73E-13
EP	6.85E-13	9.90E-15	1.52E-14	5.62E-14	4.23E-14	8.76E-14

Table C2. *Normalization results of the baseline building in SimaPro - continued*

Impact Category	**Prefinished engineered wood flooring, at engineered wood flooring plant, E/m3/RNA**	**Glued laminated timber, for indoor use {GLO}| market for | Alloc Rec, U**	**Window frame, poly vinyl chloride, U=1.6 W/m2K {GLO}| market for | Alloc Rec, U**	**Glazing, double, U<1.1 W/m2K {GLO}| market for | Alloc Rec, U**	**Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, U**	**Coating powder {GLO}| market for | Alloc Rec, U**
ADP-FF	3.90E-14	1.54E-15	8.31E-13	2.99E-13	2.88E-15	4.07E-14
GWP	2.49E-14	9.91E-16	4.49E-13	2.38E-13	1.73E-15	2.70E-14
ODP	4.29E-16	2.37E-17	3.13E-15	4.80E-15	2.86E-17	3.10E-16
POFP	2.85E-14	6.66E-16	1.47E-13	8.41E-14	1.22E-15	2.95E-14
AP	3.89E-14	1.06E-15	4.39E-13	3.20E-13	2.30E-15	2.96E-14
EP	3.64E-15	4.97E-16	2.14E-13	8.02E-14	7.93E-16	1.12E-14

Table C2. *Normalization results of the baseline building in SimaPro - continued*

Impact Category	**Acrylic filler {GLO}| market for | Alloc Rec, U**	**Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Alloc Rec, U**	**Cement mortar {CH}| market for cement mortar | Alloc Rec, U**	**Gas boiler {GLO}| market for | Alloc Rec, U**	**Pump, 40W {GLO}| market for | Alloc Rec, U**	**Tap water {RER}| market group for | Alloc Rec, U**
ADP-FF	8.26E-16	3.48E-15	1.66E-15	3.95E-15	4.76E-15	3.83E-18
GWP	3.83E-16	2.93E-15	3.42E-15	3.34E-15	4.04E-15	3.01E-18
ODP	7.18E-18	4.44E-17	2.60E-17	3.37E-17	3.93E-17	5.84E-20
POFP	2.33E-16	2.03E-15	5.29E-16	2.21E-15	3.72E-15	7.63E-19
AP	4.08E-16	3.55E-15	1.48E-15	5.46E-15	1.11E-14	2.65E-18
EP	1.33E-16	1.57E-15	5.69E-16	4.76E-15	9.89E-15	2.16E-18

Table C2. *Normalization results of the baseline building in SimaPro - continued*

Impact Category	**Natural gas, high pressure {GR}| import from RU | Alloc Rec, U**	**Electricity, low voltage {TR}| market for | Alloc Rec, U**	**Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Rec, U**	**Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Rec, U**	**Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Alloc Rec, U**
ADP-FF	4.06E-11	1.12E-10	7.04E-14	1.79E-14	2.12E-12
GWP	7.18E-12	8.27E-11	3.77E-14	1.05E-14	1.20E-12
ODP	1.03E-12	2.82E-13	1.41E-15	3.63E-16	4.33E-14
POFP	2.88E-12	2.06E-11	5.80E-15	1.39E-15	2.04E-13
AP	5.80E-12	7.96E-11	1.51E-14	3.40E-15	8.78E-13
EP	1.60E-12	6.44E-11	3.72E-15	7.26E-16	2.74E-13

D. Characterization and Normalization Results of the Case Study Building in SimaPro (2)

Table D1. *Characterization results of the case study building in SimaPro (2)*

<table>
<tr><th>Impact Category</th><th>Concrete, 35MPa {GLO}| market for | Alloc Rec, U</th><th>Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S</th><th>Reinforcing steel {GLO}| market for | Alloc Def, U</th><th>Galvanized steel sheet, at plant/RNA</th><th>Autoclaved aerated concrete block {GLO}| market for | Alloc Rec, U</th><th>Steel, low-alloyed {GLO}| market for | Alloc Def, U</th></tr>
<tr><td>ADP (MJ)</td><td>5.63E+02</td><td>1.65E+01</td><td>5.49E+02</td><td>1.75E+02</td><td>3.59E+01</td><td>6.40E+02</td></tr>
<tr><td>GWP (kg CO_2)</td><td>9.52E+01</td><td>1.59E+00</td><td>5.67E+01</td><td>1.72E+01</td><td>5.79E+00</td><td>6.49E+01</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>4.70E-06</td><td>0.00E+00</td><td>3.02E-06</td><td>4.75E-08</td><td>2.78E-07</td><td>3.34E-06</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>9.07E-03</td><td>7.22E-04</td><td>3.22E-02</td><td>5.28E-03</td><td>7.49E-04</td><td>3.41E-02</td></tr>
<tr><td>AP (kg SO_2)</td><td>2.12E-01</td><td>4.88E-03</td><td>2.43E-01</td><td>3.35E-02</td><td>1.36E-02</td><td>3.08E-01</td></tr>
<tr><td>EP (kg PO_4)</td><td>6.03E-02</td><td>3.37E-04</td><td>1.18E-01</td><td>-2.00E-02</td><td>3.31E-03</td><td>2.18E-01</td></tr>
</table>

Table D1. *Characterization results of the case study building in SimaPro (2) - continued*

<table>
<tr><th>Impact Category</th><th>Cladding, crossbar-pole, aluminium {GLO}| market for | Alloc Def, U</th><th>Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m3 RER S</th><th>Gypsum plasterboard {GLO}| market for | Alloc Rec, U</th><th>Ceramic tile {GLO}| market for | Alloc Rec, U</th><th>Single-ply, white, polyester reinforced PVC roofing membrane, 48 mils (1.219 mm)/m2/RNA</th><th>Natural stone plate, polished {GLO}| market for | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>7.01E+02</td><td>2.27E+01</td><td>1.84E+01</td><td>8.10E+01</td><td>2.04E+01</td><td>8.87E+01</td></tr>
<tr><td>GWP (kg CO_2)</td><td>6.59E+01</td><td>2.08E+00</td><td>1.74E+00</td><td>6.26E+00</td><td>9.36E-01</td><td>7.52E+00</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>4.88E-06</td><td>1.06E-07</td><td>8.96E-08</td><td>5.32E-07</td><td>7.78E-08</td><td>5.62E-07</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>2.57E-02</td><td>6.51E-04</td><td>4.93E-04</td><td>1.96E-03</td><td>5.96E-04</td><td>1.50E-03</td></tr>
<tr><td>AP (kg SO_2)</td><td>3.83E-01</td><td>1.52E-02</td><td>1.11E-02</td><td>3.30E-02</td><td>9.80E-03</td><td>4.12E-02</td></tr>
<tr><td>EP (kg PO_4)</td><td>1.06E-01</td><td>1.57E-03</td><td>2.40E-03</td><td>8.90E-03</td><td>6.70E-03</td><td>1.39E-02</td></tr>
</table>

Table D1. *Characterization results of the case study building in SimaPro (2) - continued*

<table>
<tr><th>Impact Category</th><th>Prefinished engineered wood flooring, at engineered wood flooring plant, E/m3/RNA</th><th>Glued laminated timber, for indoor use {GLO}| market for | Alloc Rec, U</th><th>Window frame, aluminium, U=1.6 W/m2K {GLO}| market for | Alloc Rec, U</th><th>Glazing, triple, U<0.5 W/m2K {GLO}| market for | Alloc Rec, U</th><th>Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, U</th><th>Coating powder {GLO}| market for | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>1.48E+01</td><td>5.87E-01</td><td>5.97E+02</td><td>1.89E+02</td><td>1.10E+00</td><td>1.55E+01</td></tr>
<tr><td>GWP (kg CO_2)</td><td>1.04E+00</td><td>4.15E-02</td><td>6.16E+01</td><td>1.68E+01</td><td>7.23E-02</td><td>1.13E+00</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>9.73E-08</td><td>5.36E-09</td><td>2.22E-06</td><td>1.27E-06</td><td>6.48E-09</td><td>7.02E-08</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>1.05E-03</td><td>2.45E-05</td><td>2.19E-02</td><td>4.96E-03</td><td>4.50E-05</td><td>1.09E-03</td></tr>
<tr><td>AP (kg SO_2)</td><td>9.28E-03</td><td>2.53E-04</td><td>3.53E-01</td><td>1.23E-01</td><td>5.50E-04</td><td>7.07E-03</td></tr>
<tr><td>EP (kg PO_4)</td><td>5.76E-04</td><td>7.86E-05</td><td>8.38E-02</td><td>2.22E-02</td><td>1.25E-04</td><td>1.77E-03</td></tr>
</table>

Table D1. *Characterization results of the case study building in SimaPro (2) - continued*

Impact Category	**Acrylic filler {GLO}| market for | Alloc Rec, U**	**Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Alloc Rec, U**	**Cement mortar {CH}| market for cement mortar | Alloc Rec, U**	**Gas boiler {GLO}| market for | Alloc Rec, U**	**Flat plate solar collector, Cu absorber {GLO}| market for | Alloc Rec, U**	**Photovoltaic panel, single-Si wafer {GLO}| market for | Alloc Rec, U**
ADP (MJ)	3.14E-01	1.32E+00	6.30E-01	1.50E+00	1.45E+01	1.60E+03
GWP (kg CO_2)	1.60E-02	1.22E-01	1.43E-01	1.40E-01	1.42E+00	1.40E+02
ODP (kg CFC-11)	1.63E-09	1.01E-08	5.89E-09	7.65E-09	8.32E-08	2.27E-05
POFP (kg C_2H_4)	8.57E-06	7.45E-05	1.94E-05	8.11E-05	9.18E-04	3.43E-02
AP (kg SO_2)	9.73E-05	8.48E-04	3.52E-04	1.30E-03	1.95E-02	7.39E-01
EP (kg PO_4)	2.11E-05	2.48E-04	9.00E-05	7.54E-04	9.83E-03	2.98E-01

Table D1. *Characterization results of the case study building in SimaPro (2) - continued*

<table>
<tr><th>Impact Category</th><th>Pump, 40W {GLO}| market for | Alloc Rec, U</th><th>Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {GLO}| market for | Alloc Rec, U</th><th>Absorption chiller, 100kW {GLO}| market for | Alloc Rec, U</th><th>Rainwater system</th><th>Greywater system</th><th>Tap water {RER}| market group for | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>1.81E+00</td><td>7.41E+01</td><td>2.94E+01</td><td>6.76E-03</td><td>1.52E-02</td><td>4.95E-04</td></tr>
<tr><td>GWP (kg CO_2)</td><td>1.69E-01</td><td>7.24E+00</td><td>2.77E+00</td><td>9.20E-04</td><td>1.49E-03</td><td>4.28E-05</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>8.90E-09</td><td>3.39E-07</td><td>1.51E-07</td><td>4.50E-11</td><td>7.65E-11</td><td>4.51E-12</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>1.37E-04</td><td>2.41E-03</td><td>1.91E-03</td><td>1.20E-07</td><td>9.20E-07</td><td>9.55E-09</td></tr>
<tr><td>AP (kg SO_2)</td><td>2.66E-03</td><td>4.21E-02</td><td>3.37E-02</td><td>2.61E-06</td><td>6.16E-06</td><td>2.15E-07</td></tr>
<tr><td>EP (kg PO_4)</td><td>1.56E-03</td><td>1.13E-02</td><td>1.98E-02</td><td>7.35E-07</td><td>2.39E-06</td><td>1.17E-07</td></tr>
</table>

Table D1. *Characterization results of the case study building in SimaPro (2) - continued*

<table>
<tr><th>Impact Category</th><th>Natural gas, high pressure {GR}| import from RU | Alloc Rec, U</th><th>Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Rec, U</th><th>Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Rec, U</th><th>Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Def, U</th><th>Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Alloc Def, U</th><th>Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Alloc Rec, U</th></tr>
<tr><td>ADP (MJ)</td><td>1.33E+04</td><td>2.68E+01</td><td>9.33E+00</td><td>-5.89E+01</td><td>-1.12E+03</td><td>3.62E+01</td></tr>
<tr><td>GWP (kg CO_2)</td><td>2.59E+02</td><td>1.58E+00</td><td>6.03E-01</td><td>-6.77E+00</td><td>-1.25E+02</td><td>2.26E+00</td></tr>
<tr><td>ODP (kg CFC-11)</td><td>2.02E-04</td><td>3.20E-07</td><td>1.13E-07</td><td>-1.80E-07</td><td>-5.37E-06</td><td>4.41E-07</td></tr>
<tr><td>POFP (kg C_2H_4)</td><td>9.13E-02</td><td>2.13E-04</td><td>6.99E-05</td><td>-2.41E-03</td><td>-8.42E-02</td><td>3.37E-04</td></tr>
<tr><td>AP (kg SO_2)</td><td>1.20E+00</td><td>3.59E-03</td><td>1.11E-03</td><td>-3.99E-02</td><td>-5.03E-01</td><td>9.41E-03</td></tr>
<tr><td>EP (kg PO_4)</td><td>2.19E-01</td><td>5.89E-04</td><td>1.57E-04</td><td>-8.98E-03</td><td>-1.50E-01</td><td>1.95E-03</td></tr>
</table>

Table D2. Normalization results of the case study building in SimaPro (2)

Impact Category	Concrete, 35MPa {GLO}| market for | Alloc Rec, U	Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S	Reinforcing steel {GLO}| market for | Alloc Def, U	Galvanized steel sheet, at plant/RNA	Autoclaved aerated concrete block {GLO}| market for | Alloc Rec, U	Steel, low-alloyed {GLO}| market for | Alloc Def, U
ADP-FF	1.48E-12	4.33E-14	1.44E-12	4.61E-13	9.43E-14	1.68E-12
GWP	2.27E-12	3.81E-14	1.35E-12	4.11E-13	1.38E-13	1.55E-12
ODP	2.07E-14	0	1.33E-14	2.09E-16	1.23E-15	1.47E-14
POFP	2.47E-13	1.96E-14	8.77E-13	1.44E-13	2.04E-14	9.29E-13
AP	8.87E-13	2.05E-14	1.02E-12	1.40E-13	5.70E-14	1.29E-12
EP	3.81E-13	2.13E-15	7.49E-13	-1.26E-13	2.09E-14	1.38E-12

Table D2. *Normalization results of the case study building in SimaPro (2) - continued*

<table>
<tr><th>Impact Category</th><th>Cladding, crossbar-pole, aluminium {GLO}| market for | Alloc Def, U</th><th>Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m3 RER S</th><th>Gypsum plasterboard {GLO}| market for | Alloc Rec, U</th><th>Ceramic tile {GLO}| market for | Alloc Rec, U</th><th>Single-ply, white, polyester reinforced PVC roofing membrane, 48 mils (1.219 mm)/m2/RNA</th><th>Natural stone plate, polished {GLO}| market for | Alloc Rec, U</th></tr>
<tr><td>ADP-FF</td><td>1.84E-12</td><td>5.97E-14</td><td>4.85E-14</td><td>2.13E-13</td><td>5.36E-14</td><td>2.33E-13</td></tr>
<tr><td>GWP</td><td>1.58E-12</td><td>4.97E-14</td><td>4.17E-14</td><td>1.50E-13</td><td>2.24E-14</td><td>1.80E-13</td></tr>
<tr><td>ODP</td><td>2.15E-14</td><td>4.66E-16</td><td>3.95E-16</td><td>2.35E-15</td><td>3.43E-16</td><td>2.48E-15</td></tr>
<tr><td>POFP</td><td>6.99E-13</td><td>1.77E-14</td><td>1.34E-14</td><td>5.34E-14</td><td>1.62E-14</td><td>4.08E-14</td></tr>
<tr><td>AP</td><td>1.60E-12</td><td>6.38E-14</td><td>4.66E-14</td><td>1.38E-13</td><td>4.11E-14</td><td>1.73E-13</td></tr>
<tr><td>EP</td><td>6.70E-13</td><td>9.90E-15</td><td>1.52E-14</td><td>5.62E-14</td><td>4.23E-14</td><td>8.76E-14</td></tr>
</table>

Table D2. *Normalization results of the case study building in SimaPro (2) - continued*

Impact Category	**Prefinished engineered wood flooring, at engineered wood flooring plant, E/m3/RNA**	**Glued laminated timber, for indoor use {GLO}| market for | Alloc Rec, U**	**Window frame, aluminium, U=1.6 W/m2K {GLO}| market for | Alloc Rec, U**	**Glazing, triple, U<0.5 W/m2K {GLO}| market for | Alloc Rec, U**	**Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, U**	**Coating powder {GLO}| market for | Alloc Rec, U**
ADP-FF	3.90E-14	1.54E-15	1.57E-12	4.96E-13	2.88E-15	4.07E-14
GWP	2.49E-14	9.91E-16	1.47E-12	4.03E-13	1.73E-15	2.70E-14
ODP	4.29E-16	2.37E-17	9.80E-15	5.61E-15	2.86E-17	3.10E-16
POFP	2.85E-14	6.66E-16	5.95E-13	1.35E-13	1.22E-15	2.95E-14
AP	3.89E-14	1.06E-15	1.48E-12	5.15E-13	2.30E-15	2.96E-14
EP	3.64E-15	4.97E-16	5.29E-13	1.40E-13	7.93E-16	1.12E-14

Table D2. *Normalization results of the case study building in SimaPro (2) - continued*

Impact Category	**Acrylic filler {GLO}| market for | Alloc Rec, U**	**Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Alloc Rec, U**	**Cement mortar {CH}| market for cement mortar | Alloc Rec, U**	**Gas boiler {GLO}| market for | Alloc Rec, U**	**Flat plate solar collector, Cu absorber {GLO}| market for | Alloc Rec, U**	**Photovoltaic panel, single-Si wafer {GLO}| market for | Alloc Rec, U**
ADP-FF	8.26E-16	3.48E-15	1.66E-15	3.95E-15	3.82E-14	4.22E-12
GWP	3.83E-16	2.93E-15	3.42E-15	3.34E-15	3.40E-14	3.35E-12
ODP	7.18E-18	4.44E-17	2.60E-17	3.37E-17	3.67E-16	1.00E-13
POFP	2.33E-16	2.03E-15	5.29E-16	2.21E-15	2.50E-14	9.32E-13
AP	4.08E-16	3.55E-15	1.48E-15	5.46E-15	8.17E-14	3.10E-12
EP	1.33E-16	1.57E-15	5.69E-16	4.76E-15	6.21E-14	1.88E-12

Table D2. *Normalization results of the case study building in SimaPro (2) - continued*

Impact Category	**Pump, 40W {GLO}| market for | Alloc Rec, U**	**Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {GLO}| market for | Alloc Rec, U**	**Absorption chiller, 100kW {GLO}| market for | Alloc Rec, U**	**Rainwater system**	**Greywater system**	**Tap water {RER}| market group for | Alloc Rec, U**
ADP-FF	4.76E-15	1.95E-13	7.72E-14	1.78E-17	3.98E-17	1.30E-18
GWP	4.04E-15	1.73E-13	6.63E-14	2.20E-17	3.56E-17	1.02E-18
ODP	3.93E-17	1.50E-15	6.67E-16	1.99E-19	3.37E-19	1.99E-20
POFP	3.72E-15	6.55E-14	5.21E-14	3.27E-18	2.50E-17	2.60E-19
AP	1.11E-14	1.77E-13	1.41E-13	1.09E-17	2.58E-17	9.01E-19
EP	9.89E-15	7.16E-14	1.25E-13	4.64E-18	1.51E-17	7.37E-19

Table D2. *Normalization results of the case study building in SimaPro (2) - continued*

<table>
<tr><th>Impact Category</th><th>Natural gas, high pressure {GR}| import from RU | Alloc Rec, U</th><th>Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Rec, U</th><th>Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Rec, U</th><th>Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Def, U</th><th>Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Alloc Def, U</th><th>Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Alloc Rec, U</th></tr>
<tr><td>ADP-FF</td><td>3.51E-11</td><td>7.04E-14</td><td>2.45E-14</td><td>-1.55E-13</td><td>-2.95E-12</td><td>2.18E-12</td></tr>
<tr><td>GWP</td><td>6.20E-12</td><td>3.77E-14</td><td>1.44E-14</td><td>-1.62E-13</td><td>-2.99E-12</td><td>1.24E-12</td></tr>
<tr><td>ODP</td><td>8.90E-13</td><td>1.41E-15</td><td>4.98E-16</td><td>-7.93E-16</td><td>-2.37E-14</td><td>4.46E-14</td></tr>
<tr><td>POFP</td><td>2.48E-12</td><td>5.80E-15</td><td>1.90E-15</td><td>-6.55E-14</td><td>-2.29E-12</td><td>2.10E-13</td></tr>
<tr><td>AP</td><td>5.01E-12</td><td>1.51E-14</td><td>4.66E-15</td><td>-1.67E-13</td><td>-2.11E-12</td><td>9.03E-13</td></tr>
</table>