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INTEGRATING THE ENVIRONMENTAL IMPACT OF GREEN TECHNOLOGIES IN CONSTRUCTION PROJECT MANAGEMENT

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Preface

In order to complete my degree in Business Engineering with major in Operations Management at Ghent University, I wrote this thesis. Choosing a subject was not a time-consuming quest for me. During my studies, I already found project management very interesting. The combination with sustainability and construction seemed ideal for me to delve into. The construction sector is a major contributor to global environmental problems. Hence, there is enormous potential to address sustainability in construction projects, such as working with alternative materials, rethinking design, implementing sustainable technologies and so on. These are all fascinating avenues to explore in my opinion, but in this thesis I will focus on green technologies. This particularly appealed to me because, on the one hand, they are promising to reduce greenhouse gas emissions, but on the other hand, critics have doubts about certain green technologies, for example because their production is highly polluting (e.g. wind turbines). This seemed very interesting to include in my thesis which integrates the environmental impact of these technologies into project management processes and practices. My literature review shows that I am not the only one who find these concepts intriguing. Several academics have already conducted research in this area and even companies and other institutions are embracing sustainability in their projects. I sincerely hope that my work will contribute to a more sustainable building stock.

I would also like to take this moment to express my gratitude to some people who were crucial while writing my thesis. First of all, I would like to express my deepest gratitude to my promotor prof. dr. ir. Mario Vanhoucke and commissioner dr. Tom Servranckx. I am grateful for sharing their knowledge, experience and enthusiasm with me. Furthermore, your confidence, advice and tailored recommendations have allowed me to proudly realise this thesis.

In addition, I acknowledge gratitude to Charlotte Dossche for sharing her knowledge about life cycle assessments and her practical experiences with sustainability in the construction industry. I appreciate your critical thinking and helpfulness.

I would also like to express my gratitude to my boyfriend, my friends and my parents. Thank you for your moral support during my thesis trajectory. Because of my enthusiasm on the subject, I sometimes lost myself in explaining it. Nevertheless, I hope that they will remember some interesting and valuable insights and that the subject will fascinate them as well.

Through the construction of my parents' house, I came into contact with some craftsmen in the construction sector. Finally, my special thanks also go to architect Patrick Loete, heat pump installer Kenneth Dobbelaere and contractor Jean-Paul Nuyt for their excellent work and sharing their knowledge with me.

I sincerely wish you much reading enjoyment!

Gaël Minnaert
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Introduction

Integrating the environmental impact of green technologies into construction project management is an important step towards a more sustainable world. The construction industry in particular has a major impact on global environmental problems, making action urgently needed. By providing project managers/teams with information and a clear framework, we hope this work will contribute to a more sustainable world. The European Green Deal had a promising overarching objective to make Europe the world's first climate-neutral continent by 2050, including by developing cleaner energy sources and green technologies (European Commission, 2022b). One of the key principles for a transition to clean energy targeted by the European Green Deal was to prioritise energy efficiency, improving the energy performance of buildings and using renewable energy sources (European Commission, 2022a).

The evolution of environmental and energy policies has and will undoubtedly have a major impact on the construction industry in the future. The present contribution of the construction industry to global environmental problems and climate change cannot be underestimated. Currently, this sector, together with the material industries that support it, is one of the world's largest exploiters of natural resources (Spence & Mulligan, 1995). Globally, the construction sector is responsible for slightly over one-third of global greenhouse gas emissions and for approximately 40% of total global annual energy consumption, of which 80% originates from fossil fuels (CIC, 2022; European Commission, nd; Huaman & Xiu Jun, 2014; Mahmoud et al., 2019; Neill, 2020; Nejat et al., 2015; Omer, 2008a; UNEP, 2022; United Nations, 2016; Ürge Vorsatz et al., 2007). Moreover, the construction sector in the European Union accounts for more than 35% of total waste generation and for roughly 50% of all extracted material (European Commission, nd). The impact of buildings occurs in all phases of their life cycle, but mainly in the operation and maintenance phase, which accounts for 70% to 90% of all environmental impacts of buildings throughout their life cycle (Mahmoud et al., 2019; Seppo, 2004; UNEP, 2009; Yılmaz & Bakış, 2015). Consequently, we can conclude that the construction industry has a significant impact on the environment, making the need to reduce the environmental impact of construction activities increasingly urgent.

Improving the sustainability of buildings results in many positive impacts that are critical, such as helping to reduce greenhouse gas emissions and associated side effects, helping to reduce air pollution, improving health and quality of life, increasing productivity, creating jobs and new business opportunities, improving social welfare and poverty reduction, and increasing energy security (Mahmoud et al., 2019; UNEP, 2009; IPCC, 2007). To facilitate these improvements, it is vital to gain a better understanding of building sustainability. This emphasises the need for sustainability assessment tools to assess the performance of buildings, reduce their harmful effects on the environment and encourage project teams to improve the performance of their buildings by considering economic, environmental and social aspects (Al Waer & Sibley, 2005; Mahmoud et al., 2019). It is this need that we are going to respond to in this thesis. However, we have limited its scope to the environmental impact of green technologies in construction projects. Green technologies have emerged as a promising avenue to reduce the environmental impact of construction projects. These technologies include both renewable energy systems, such as solar panels and wind turbines, and energy-efficient systems, such as heat pumps. Nevertheless, despite their potential benefits, their environmental impact is not sufficiently factored into the decision making of project teams.

The objective of this master's thesis is to investigate how the environmental impact of green technologies can be integrated into construction project management. Our thesis is divided into five chapters. The first two chapters cover literature reviews on sustainability in project management and green technologies in construction. While in the first chapter we discuss sustainability with all its pillars, we limit ourselves afterwards to the environmental pillar. In the third chapter, we discuss sustainability assessment systems and elaborate on life cycle analysis (LCA), which we will apply in the fourth chapter. This method allows us to measure and compare the environmental impact of certain technologies, such as heat pumps and solar-powered systems. In the final chapter, we discuss a well-defined framework after which we apply it to a case study in the construction industry. We convert the calculated environmental impact into e-scores and discuss various possibilities regarding its evolution. Based on these scores, we aim to integrate sustainability into project team decisions.

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Sustainability in Project Management

Integrating sustainability into construction project management requires a deep understanding of both disciplines. Moreover, the extent to which the two disciplines are already interconnected is fascinating. This chapter is therefore divided into three sections. In the first section, we elaborate on the concepts of sustainability and sustainable development. We start from the fundamentals and explore the evolution of sustainable development, highlighting some influential events. Subsequently, we delve into the core principles and dimensions of sustainability, highlighting the need for a holistic approach that considers environmental, social and economic aspects. The second section focuses on project management, where we discuss the evolution of project management and then move on to project success and the criteria required to achieve it. By better understanding these two disciplines separately, we can identify the opportunities and challenges associated with integrating sustainability into project management practices. In the third section we discuss the relationship between sustainable development and project management. We discuss some of the areas where sustainability has an impact on project management practices. Finally, we highlight the importance and relevance of integrating sustainability, particularly in the construction sector.

1.1 Sustainable development

Many policy makers, companies and other institutions claim to pay significant attention to sustainability and use sustainable development as an attractive catchphrase, but what exactly does it mean? Unfortunately, we will not be able to give a clear answer. An extensive literature study taught us that its history and meaning, as well as the method of measurement and the implications for human development, still raises many questions (Mensah, 2019; Ruggerio, 2021; Tuazon et al., 2013).

To elaborate on this, it is important to clarify the differences between "sustainability" and "sustainable development". Unfortunately, we cannot approach the concepts the way physical scientists approach a standard kilogram. In the academic literature there is also much discussion about these two concepts and no consensus has has been reached (yet). Diesendorf (2000) and Gray (2010) envisioned sustainability as the goal or endpoint of a process called sustainable development. In this rationale, sustainability refers to a state, while sustainable development refers to the process of achieving that state. In their review paper on sustainability, Waas et al. (2011) referred to another view to clarify the difference. During their research, they noticed that some scholars argue that sustainable development is primarily about economic growth/development, while sustainability prioritises the environment. The difference in this belief lies in the fact that sustainable development "ameliorates" the environment , while sustainability is about "challenging" economic growth, focusing on humanity's ability to live within the environmental limits of the planet (Waas et al., 2011). Since the debate remains unsolved regarding how the terms differ and even whether the terms differ (Gibson et al., 2001; Tuazon et al., 2013; Waas et al., 2011), we will use both terms interchangeably throughout this thesis.

First, we briefly consider how sustainable development has evolved and been managed. This allows us to understand the foundations of the concept, which facilitates the integration of sustainable development into project management. Among the multitude of definitions found in the literature of sustainability or sustainable development, there is an almost constant focus on the interconnection of three pillars, namely the environmental one, the economic one and the social one. These pillars are interconnected and involve trade-offs, which we will also elaborate on.

1.1.1 Evolution sustainable development

The deep roots of sustainability (Purvis et al., 2019) date back to the 17th and 18th centuries, but it took until the 1980s for it to emerge into the mainstream. Half a century ago, the United Nations (UN) began to recognise sustainability and the human impact on the environment as a global problem through the Stockholm Convention (1972) (Handl, 2012; Tuazon et al., 2013). The most often cited definition of the concept dates from several years later and was proposed by the World Commission on Environment and Development, also called the Brundtland Commission. In 1987, they published the report "Our Common Future" (WCED,1987) in which sustainable development was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Although the world's political and environmental landscape has changed significantly, the publication of this report marked a turning point in thinking about environment, development and governance (Sneddon et al., 2006).

According to Jain & Islam (2015), the Brundtland report engendered the United Nations Conference on Environment and Development (UNCED) in 1992, often known as the Rio Earth Summit. The recommendations made in the Brundtland report formed primary topics of debate at the UNCED. One of the key outcomes of the UNCED was Agenda 21, a comprehensive plan of action calling for new strategies for investing in the future to achieve overall sustainable development in the 21st century (United Nations, nda). This official worldwide consensus on development and environmental cooperation, approved by 178 countries, urged all states to take on their common responsibility to participate in improving, protecting and better managing ecosystems (United Nations, ndb). At the Earth Summit in Rio (United Nations, nda), there was a growing awareness that integrating and balancing economic, social and environmental considerations in meeting our needs is essential to sustaining human life on the planet. It was a universal trend that sustainable development was increasingly seen as an integrated system consisting of these three dimensions, namely economic, social and environmental (Heng, 2011). The conference also recognised that integrating and balancing these three dimensions requires new perceptions of the way we produce and consume, the way we live and work, and the way we make decisions (United Nations, nda). The book "Sustainability after Rio" (Crowther & Islam, 2015) covers some more important achievements of the conference. The conference resulted in an agreement on the Climate Change Convention that in turn led to the Kyoto Protocol. At the Kyoto conference in 1997, a promising target was agreed by developed countries on specific targets for cutting their emissions of greenhouse gases for the period 2008-2012 (Paul, 2008). Unfortunately, these targets have not been met, which raises the question of whether Kyoto has made a difference to the counterfactual scenario of "no Kyoto" (Aichele & Felbermayr, 2013).

Since sustainable development is clearly not a fixed state of harmony, but rather can be considered as a process of change (Massey, 2007), it is certainly interesting to consider the key take-aways of subsequent UN-conferences as well. Eight years later, at the Millennium Summit in September 2000, eight Millennium Development Goals (MDGs) (Paul, 2008; United Nations, ndd) were set out, which represent a more practical impression of the principle of equilibrium between the economic, social and environmental pillars of sustainable development. The MDGs include eradicating extreme poverty and hunger, achieving universal primary education, promoting gender equality and women's empowerment, reducing child mortality, improving maternal health, combating HIV/AIDS, malaria and other diseases, ensuring a sustainable environment and developing a global partnership for development (United Nations, 2000a,b, ndc).

A subsequent milestone was the World Summit on Sustainable Development (WSSD) in Johannesburg 2002, which built on Agenda 21 and the Millennium Declaration by placing greater emphasis on multilateral partnerships (Mensah, 2019). The partnerships between the United Nations, governments, business and NGOs are instrumental in raising resources to address environmental, health and poverty challenges (Paul, 2008). The WSSD addresses a number of newly emerging issues including the lack of access to basic sanitation, harmful effects of chemicals, the depleted fish stocks and so on (Paul, 2008).

In 2012, two decades after the Earth Summit in Rio, the Member States at the United Nations Conference on Sustainable Development (Rio+20) adopted the outcome document "The Future We Want" (United Nations, ndd). This included a process to start developing a set of sustainable development goals (SDGs) as well as other measures for implementing sustainable development, including mandates for future work programmes in development finance, small island developing states and more (Messerli et al., 2019; United Nations, ndd).

In terms of multilateralism and international policy making, we can certainly call 2015 a landmark year with the adoption of several key agreements (United Nations, ndd) such as the 2030 Agenda for Sustainable Development with its 17 SDGs and the Paris Agreement on Climate Change. The contribution of these documents is certainly not to be underestimated. The adoption of the 2030 Agenda for Sustainable Development at the UN Sustainable Development Summit in New York (2015) was a key moment in building a consensus for urgent, inclusive action (Messerli et al., 2019). The goals (Madeley, 2015; United Nations, nde), adopted by the United Nations, are very ambitious as they aim to end poverty, end hunger, ensure healthy lives and promote well-being, ensure inclusive and equitable education, achieve gender equality, ensure access to clean water and sanitation and to affordable and clean energy. The SDGs also promote sustainable economic growth and decent work, build resilient infrastructure, foster innovation and industrialisation, reduce inequalities and aim for sustainable cities and communities. In addition, they pursue sustainable consumption and production patterns, take action to combat climate change, conserve life below water and protect, restore and promote life on land. The last two goals cover peace, justice and strong institutions as well as the global partnership for sustainable development. In recent years, many action programmes, measurement and performance frameworks supported these SDGs and no effort was spared, but it does not look like we will achieve the SDGs by 2030 (Bebbington & Unerman, 2018; Messerli et al., 2019). In order to continue the transformation, it is necessary that not only states but also other relevant stakeholders, from businesses and labour unions to civil society and academia, understand and engage the scientific reality in order to take action (Messerli et al., 2019).

Based on these important conferences, international agreements, publications, goal settings and so on, we can draw some interesting conclusions. We notice a shift from a primary emphasis on environmental issues to a shared focus on ecological, social and economic development. For this thesis mainly ecological development is relevant, but for the sake of completeness we treat sustainable development as an integrated system of three pillars. We will discuss this briefly in section 1.1.2.

The United Nations conferences have had a major impact on the evolution of the 'sustainable development' concept. These international conferences attracted much attention, funding and stimulated the development of networks to address together the challenges of the Industrial Revolution. The agreements forged by many Member States of the United Nations were the beginning of the path to a world with less poverty, less inequality, less conflict, less emissions and so on. In short, they provided the path to a world where people should be able to enjoy their fundamental rights and freedoms now, but certainly in the future. It is now our responsibility to make this path a reality. For more interesting information about the United Nations and the thematic conferences they hold, we refer interested readers to their site (United Nations, ndf).

1.1.2 Three pillars of sustainable development

In order to clarify the three pillars of sustainable development, we will first review their conceptual foundations. Subsequently, we will reflect on the number of pillars and finally, we will briefly discuss why sustainable development is so difficult to translate into policy.

Conceptual foundations

As outlined in the chapter above, over time, sustainable development was increasingly perceived as an integrated system consisting of three pillars, namely social, economic and environmental (Heng, 2011). However, if we search for the conceptual foundations of this model, they are far from clear and theoretical underpinnings of the three-pillar paradigm are lacking (Purvis et al., 2019). While some sources have attributed the origins of the 'three-pillar paradigm' to the Brundtland Report, Agenda 21 and the 2002 World Summit on Sustainable Development, none of these publications have made a clear framework or theoretical background explicit (Purvis et al., 2019).

Even in the business and management world, they can no longer avoid the complex and multi-dimensional concept of sustainable development. The Triple Bottom Line (TBL), which is formed by the 3Ps, namely People, Planet and Profit is coined by Elkington in the 1990s (Elkington, 1994, 1997, 2013). The idea behind this paradigm is that the ultimate success or health of a corporation can and should be measured not only by its financial, but also by its social/ethical and environmental performance (Norman & MacDonald, 2004). As a result, companies are encouraged to take long-term perspectives into account during their decision making. In theory, this sounds an intriguing rationale, but unfortunately there is little evidence that it is used effectively. In fact, Norman & MacDonald (2004) argue that the concept of a TBL turns out to be a good old-fashioned single bottom line plus vague commitments to social and environmental concerns. Although the work of Elkington (1997) appears to mark the first use of three-pillar conceptualisation, this literature does not appear to be the origin of the three-pillar framework, but has certainly been influential in strengthening its position in the mainstream in the 21st century (Purvis et al., 2019). Out of this we can summarise that, unfortunately, the conceptual foundations of the three-pillar paradigm remain far from clear, as well as the point at which it entered the mainstream. This complicates the production of operational frameworks, which is certainly detrimental given the inherently political nature of sustainability (Purvis et al., 2019).

Three pillars or more?

As already explained, sustainable development seeks to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED,1987). This definition contains (implicitly) two key concepts (Huttmanová & Valentiny, 2019; Mishra, 2020; O'Neil, 2018), namely needs and constraints. By needs, we mean in particular the essential needs of the world's poor, to which decisive priority must be given. The other aspect to consider is the limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs. Each of the three dimensions always revolves around these two concepts.

First, we define **social** sustainability (Cooper et al., 2018; Munny et al., 2019), which mainly refers to the supervision of social capital and human being by integrating human and civil rights, health and safety issues, social responsibility and community spirit. Social sustainability can be considered as the purpose among the whole system of sustainable development, whereas economic sustainability is the foundation and ecological sustainability is the condition (Shen et al., 2015).

Environmental sustainability (Ranjbari et al., 2021; Roy et al., 2020) covers the management of limited resources of the biophysical world to reduce processing resources and minimise the waste generated to protect the environment and natural resources. It is relevant to each pillar, but certainly to the ecological one to keep a long-term perspective in mind. We must conserve and protect resources to remain within the Earth's environmental limits even in the distant future (Waas et al., 2011).

Similar to the two previous dimensions, the **economic** perspective (Anand & Sen, 2000; Elliott, 2005) is often seen as an issue of intergenerational equity, as it focuses on the trade-off of current and future consumption. Many authors take different approaches to defining this economic dimension. Markandya & Pearce (1988) argue that resource use today should not reduce real incomes in the future because sustainability requires that the conditions necessary for equal access to resources are met for each succeeding generation. Another approach to this dimension deals with the dependence of future economic progress on the sustained integrity of resources and the environment (Hamrin, 1983; Moldan et al., 2012). In fact, it is about sustaining the different types of capital, namely man-made, natural, human, social capital (World Bank, 2005). This is certainly relevant if we take into account population growth and the corresponding increasing human needs such as food, clothing and housing (Mensah, 2019).

These three dimensions are interconnected, which means that they cannot be viewed completely in isolation. In short, it always comes down to the same principle. In the case of economic sustainability, the key is to pursue economic growth while considering the other aspects of sustainability. Looking at it from a different perspective, the same thinking can be applied to social sustainability, which aims to alleviate poverty within the existing environmental and economic resources of society. As such, it is always about balancing the trade-offs between seemingly equally desirable goals that must also take into account fairness and equity (Elliott, 2005). It would be absurd, for example, to use up all the fish in the ocean now without taking future generations into account. This intergenerational equity lies at the heart of any definition of sustainability or one of its pillars.

The three pillars can be considered as common throughout the literature, but they are not universal. On the one hand, several studies in the literature show an inconsistent usage of sustainability since they refer or emphasise only one or two dimensions (Alhaddi et al., 2015). On the other hand, other works consider additional pillars such as institutional (Spangenberg et al., 2002; Turcu, 2013), cultural (Soini & Birkeland, 2014), technical (Hill & Bowen, 1997) or time (Waas et al., 2011).

Policy

As sustainable development integrates many aspects, it distinguishes itself from other forms of policy, which has implications for decision makers. Governments and other policy agencies are often fragmented and organised into certain sectoral ministries or departments. The three pillars of sustainable development must be integrated throughout decision-making processes, in order to push towards development that is truly sustainable (Emas, 2015).

After researching the foundations of the concept of sustainable development, there was no doubt that the United Nations played a major role in it. The international organisation has meant a lot in terms of sustainability, poverty reduction and climate change. However, since the United Nations is engaged in a wide range of activities, including development operations, but also peacekeeping and security, setting international norms and generating knowledge and statistics, there are doubts that the system is too complex and fragmented (Mahn, 2016). Certain quantitative measures conducted on the United Nations' engagement in development point in the direction of a complex web of entities with many small interventions (Mahn, 2016). This could lead to certain duplications, inefficiencies or even frustrations between certain entities. There is a heated debate going on in academia as to whether centralisation or decentralisation would be more effective for future climate governance (Ren, 2022). In the future, partly because of the emergence of the sustainable development agenda, there may be a stronger need for a more future-oriented change in the role, structure and operation of the UN development system. This could certainly be of interest for further research.

In summary, there is still more work to be done to implement sustainable development in policy processes and other activities. If we properly apply its three pillars to real-world situations, everyone wins because natural resources are conserved, the environment is protected, the economy is thriving and resilient, and social life is good because there is peace and respect for human rights (Kaivo-oja et al., 2014; Mensah, 2019). In the next section we will take a closer look at project management, after which we can examine the integration of sustainability into project management practices.

1.2 Project management

To link project management with sustainability objectives, we need to have a deep understanding of project management. We can define project management (Vanhoucke, 2012) as "the discipline of planning, organising and managing resources to bring about the successful completion of specific project goals and objectives". To gain a better understanding of project management, we will first discuss its history, followed by its more recent evolution to a more flexible approach. Subsequently, we will elaborate on the criteria that determine project success. In this regard, we wonder if sustainability is also a determinant of project success.

1.2.1 Evolution project management

The origins of project management go way back in time. In history, there are several examples of colossal projects that have been successfully completed, such as construction of the Egyptian pyramids, the Great Wall of China, the Colosseum and the Hoover Dam. We can summarise that much of the history of project management has its roots in engineering and construction projects, such as roads, railways, bridges, etc (Hall, 2012; Kabeyi, 2019). For these projects to succeed, hundreds of employees had to be managed over many years, sufficient resources were needed to support the project, it was necessary to ensure that the project was on schedule and that the end result was on time and met the commander's expectations. Unfortunately, very little documentation of these projects exists on their methods and techniques (Cleland, 2004).

From the 1950s, there is evidence that organisations began applying systematic tools and techniques to complex projects (Seymour & Hussein, 2014). Certain projects have contributed significantly to the advancement of standard practices in modern project management, such as the Manhattan Project that produced the first atomic bombs during World War II (Augustyn et al., 2023; Lenfle, 2019; Weaver, 2007). In the 1960s, other impressive projects like the Apollo moon landing project further contributed to the formation and utilisation of tools to manage large-scale projects (Seymour & Hussein, 2014). This multi-year project required the combination of 410 000 workers and had a multi-billion dollar cost (Hall, 2012). Since 1970, there have been significant technological advances that have introduced project management software and tools (Kwak, 2003). The application area of project management has become much more diverse in recent decades, and includes, for example, the implementation of new IT systems, research and development (e.g. in pharmaceuticals), the management of strategic organisational change, the development of new products and services, risk management, and software development (Hall, 2012).

The project management discipline evolves over time, but the fundamental premise never changes: "Do the thing right the first time within a reasonable time frame, with the right resources and a reasonable budget" (Knutson & Webster, 2014). Leading organisations have recognised the importance of project management and embraced project management as a tool to control costs, reduce risks and improve the organisation's projects and results (PMI, 2018c; Salameh, 2014). A survey by McKinsey reported that almost 60% of senior executives considered building a strong project management discipline (PMI, 2010b) in their organisation as one of the top-three priorities for their organisation. The importance of project management can further be explained by the complex and rapidly changing world with all its challenges, the many projects that fail, the changing customer demands, the need for multidisciplinary collaboration with different departments, organisations or institutions and so on. As a result, traditional project management is not the end point, but this discipline will certainly further evolve in the future.

In the literature, we notice an evolution from a rather inflexible to a more agile approach in project management (Ciric et al., 2019, 2022; Fernandez & Fernandez, 2009) focused on flexibility, acceptability of change, continuous advancement and high levels of interaction. Agile project management (APM) (Zasa et al., 2021) originated as a concept for software development and IT projects, but today it represents one of the fundamental competitive advantages of today's organisations. As a result, we also observed in the literature that the definitions of APM are influenced by specific software engineering and IT practices and terms, and no general clear definition of the processes and methodology has yet emerged (Salameh, 2014). Therefore, we will highlight some key aspects of APM and review why traditional project management is less suitable in some cases.

APM (Ambler, 2020; Bergmann & Karwowski, 2019) has evolved as a highly iterative and incremental process in which project teams and stakeholders actively collaborate to understand the domain, determine what needs to be built, and prioritise functionality. Due to continuous feedback on the evolving product, learning from failures and autonomous teams striving for immediate results, agile approaches are increasingly used in projects characterised by uncertainty and unpredictability (Alleman, 2005; Bergmann & Karwowski, 2019; Cicmil et al., 2006; Fernandez & Fernandez, 2009). According to research by Rico et al. (2009), projects managed with APM were found to be much more effective in terms of cost and quality than projects managed with traditional project management (TPM).

The relative ineffectiveness of TPM, especially for complex projects such as information technology (IT) and software projects, is largely due to the assumptions underpinning it (Salameh, 2014). TPM relies on some assumptions that are inconsistent with reality, such as the fact that the circumstances affecting the project are predictable and that customer requirements are clear, well understood and do not change (Ciric et al., 2019). As such, it encompasses the progression through five sequential phases: initiate, plan, execute, monitor and control, and close under the guidance and support of the project manager (PMI, 2018c). In reality, projects rarely follow a sequential flow during execution, and clients are typically unable to define all requirements at the beginning of the project (Ciric et al., 2019). Consequently, agile approaches are preferred because of their faster iterative planning and development cycles, allowing for continuous evaluation of interim results and subsequent adjustments as stakeholders desire (Bergmann & Karwowski, 2019; Hass, 2007).

Although some academics view APM and TPM as antagonistic (Alleman, 2005), many others argue that the two are not mutually exclusive but complementary (Cicmil et al., 2006; Fernandez & Fernandez, 2009; Geraldi et al., 2008; Hass, 2007; Zasa et al., 2021). Adapting TPM concepts with flexible, collaborative, adaptable but highly disciplined practices could be a decent step for improved productivity and quality (Rico, 2008; Salameh, 2014).

Until now, we have clarified the fundamentals of project management and the need for flexibility. We can now move to the project level, where we review the criteria for project success and what role sustainability plays in it.

1.2.2 Project success

The Project Management Institute (PMI) defines a project (PMI, 2000a) as "a temporary endeavour with a definite beginning and a definite end, undertaken to create a unique product or service". Although projects have a temporary character, they are always situated within a strategic context (Tharp, 2013). Understanding this context (Tharp, 2013) is important since corporate objectives are also taken into consideration when executing projects. Many leading companies even use sustainability as a market differentiator (Newman, 2020). To combat climate change and take care of the environment, it is obvious that sustainability in projects (Association for Project Management, nd) is more important than ever. Given the increasing awareness of sustainability, we wondered if sustainability is perceived as a criterion for project success.

Traditionally, project success was measured by three widely recognised criteria usually referred to as the Iron Triangle (Abdul et al., 2013), namely time, cost and quality. These three criteria (Pollack et al., 2018) are interesting because of their coherence and the associated trade-offs: movement to one criterion can put pressure on the other criteria. These criteria remain of great importance, but are no longer sufficient to provide a complete picture of the success of a construction project (Silva et al., 2016). Although project managers/teams tend to focus on short-term criteria related to the project process, the requirement of the long-term perspective on project success (Silva et al., 2016) is strongly emphasised. Taking this into account, additional criteria (Silva et al., 2016) can be defined in addition to the Iron Triangle, namely safety and cash flow management in the short term, and customer satisfaction, employees satisfaction, profitability, environmental performance and learning and development in the long term. Since projects have a limited lifetime (Schwalbe, 2015), these criteria are to facilitate the measurement of project success (Silva et al., 2016) during the execution phase and at the end of the project. The question arises whether impacts after project completion are also taken into account, such as environmental impacts during the use of a project's output, e.g. a building.

Multiple cases show that companies realise the importance of sustainability in project management (Martens & Carvalho, 2016) and that they are aware that sustainability has an impact on project success. However, there is a gap (Martens & Carvalho, 2016; Sroufe, 2017) between the intention or the perception of importance and the actual implementation in practice. It might be extremely fascinating to delve deeper into the topic of how sustainability is practically implemented in project management. Some interesting academic papers reinforce the need to explore this further, but an internet-based research would not enhance the quality of our work. Fortunately, we refer to the Discussion section on page 85 for some intriguing research papers that could serve as a starting point for an in-depth research.

Besides companies, it is also crucial that influential organisations and academics recognise and support the integration of sustainability into project management. In the next section, we continue our literature review with a focus on the integration of sustainability into project management and, more specifically, the impact areas of sustainability on project management. Subsequently, we close the loop and discuss the importance of integrating sustainability in project management and, more specifically, in construction project management. This is because the construction sector has a significant impact on the environment, which means that there is considerable potential for improvement in this sector.

1.3 Integrating sustainability in project management

Reviewing the literature indicated that both sustainability and project management are already very thoroughly researched areas, but the dualism of these two areas (Armenia et al., 2019; Martens & Carvalho, 2016) and how they interact within project dynamics deserves further attention. Our research focus is restricted to research articles with terms in the title or abstract such as 'sustainable project management' or combinations of 'sustainability', 'sustainable development' or 'green' on the one hand and 'projects' or 'project management' on the other. Our literature review indicated that this is clearly an emerging area of research as most publications on this topic date from the past 10 to 15 years. Renowned institutions or associations (e.g. Project Management Institute, Association for Project Management, International Association of Project Managers), academic bodies (e.g. CEMUS) and researchers actively support and acknowledge the importance of integrating sustainability in project management. They contribute to the advancement of sustainable practices in project management through specialised programmes, research initiatives and the inclusion of sustainability principles in frameworks and standards.

Due to its recent emergence, there is not yet a consensus on a commonly accepted definition of **'sustainable project management'**. This is not remarkable as sustainability or sustainable development also proved to be a complex and multidisciplinary concept for which different definitions with different perspectives emerged. Despite the relatively many definitions that emerge for sustainable project management, we can still identify four characteristics (Stanitsas et al., 2021) that often recur. First of all, the holistic Triple Bottom Line approach often recurs, which means not only focusing on financial gains but also reflecting social and environmental perspectives. The second characteristic focuses on long-term assessment in which the entire life cycle of the project and the project outcomes are considered. Third, we find that definitions of sustainable project management often include stakeholder engagement and management. Fourth, the ethical aspect, which encompasses the sustainability of the organisation and society as a whole, is also a recurring theme. After reviewing various definitions for sustainable project management, we find that Silvius & Schipper (2014a) propose a complete and inclusive definition:

> *"Sustainable Project Management is the planning, monitoring and controlling of project delivery and support processes, with consideration of the environmental, economic and social aspects of the life-cycle of the project's resources, processes, deliverables and effects, aimed at realising benefits for stakeholders, and performed in a transparent, fair and ethical way that includes proactive stakeholder participation."*

The relatively limited research on integrating sustainability into project management makes it a challenge in theory and practice to integrate sustainability aspects into day-to-day operations and project management (Friedrich, 2023; Peace et al., 2018). One reason for this is that sustainability is difficult to express in concrete, operational terms (Briassoulis, 2001). Silvius et al. (2017) recognised that it remains to be investigated how project teams incorporate sustainability into their operational day-to-day work. In their research, they investigate the consideration of sustainability aspects in the decision-making processes of project teams. Moreover, several publications have identified areas of impact where sustainability has an impact on project management processes and practices. We have categorised these areas of impact of the various publications into five categories that we will discuss in the following sections. These five categories are not necessarily exhaustive, but give a clear overview of the impact areas of sustainability on project management processes and practices.

Time horizon It is clear that integrating sustainability in project management (Silvius & Schipper, 2012; Silvius, 2017) may stretch the system boundaries of project management. Both temporal and spatial boundaries of the context are stretched when considering sustainability, which can be clearly seen in Figure 1.1. In this section, we will focus on the time horizon and in the next section we will move on to the spatial boundaries involving both local and global orientations. Regarding temporal boundaries, it is essential to address not only the short term but also the long term. In one of the first publications on sustainability and project management by Brent & Labuschagne (2006), it was already argued that not only the total life cycle of a project (e.g. initiation-development-execution-testing-launch) should be considered. In addition to the life cycle of the project, the result of the project is also of great importance, namely a change in products, assets, systems, processes or behaviour (Brent & Labuschagne, 2006; Silvius & Schipper, 2010). In addition to an enlarged time scale, the scope/context of the projects is broadened by both a local and a global orientation, which we will discuss in the next section.

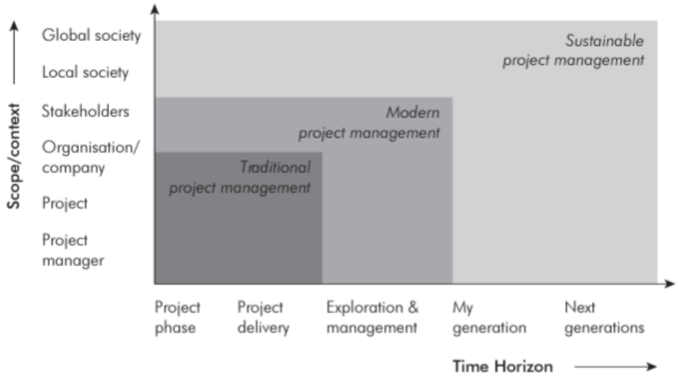


Figure 1.1: The enlarged scope of sustainable project management (Silvius & Schipper, 2014a)

Project team and stakeholders The selection and organisation of a project team (Hrvatin et al., 2022; Tharp, 2013) is important as social sustainability principles such as equal opportunities, work life balance and personal growth can be put into practice and applied by project team management. Besides the project team and project sponsor, more stakeholders are involved to integrate sustainability in project management practices. The importance of stakeholder involvement is highlighted by several authors (Gareis et al., 2010; Perrini & Tencati, 2006; Silvius & Schipper, 2019). Ideally, different levels should be taken into account ranging from local and regional to global stakeholders (Gareis et al., 2013). Silvius et al. (2012) give some examples of typical 'sustainability stakeholders', namely environmental pressure groups, human rights groups, non-governmental organisations, etc. Having more stakeholders and getting more stakeholders engaged has implications for stakeholder management and communication processes in project management. Sustainability involves transparent communication and reporting on the impact of decisions and activities on society and the environment (ISO, 2010). Following these principles, it is important to maintain proactive and open communication with all stakeholders about the project, covering both social and environmental impacts, and both the short and long term (Khalfan, 2006; Silvius & Schipper, 2014a). This differs from existing project management standards (PMI, 2018c), which reflect a reactive approach where only the necessary information is provided.

Project quality criteria and dimensions of project success Integrating sustainability into project management (Maltzman & Shirley, 2013; Silvius & Schipper, 2014a) affects the specifications and requirements for project deliverables and the criteria for project quality. Mishra et al. (2011) find that ethics in particular play a major role in the success of a particular project by gaining support from the project team and maintaining relationships with all stakeholders. In addition, the objective of a project includes environmental and other social aspects (Silvius & Schipper, 2012). As a result, the definition and perception of project success (Ika & Pinto, 2022; Silvius & Schipper, 2014a) are also changing, taking into account dimensions of sustainability such as short- and long-term economic, social and environmental aspects.

Project planning and scheduling Another area in which sustainability has an impact on the practice of project management is in the planning and scheduling of projects. By encouraging project managers/teams to think beyond how things are usually done, Taylor (2010) envisions opportunities to incorporate sustainability into project planning. For example, manufacturing off-site rather than on-site can lead to sustainability benefits such as less waste, better use of resources, opportunities to improve the skills of the workforce, opportunities to create jobs in poorer locations, economies of scale, etc (Silvius & Schipper, 2014a; Taylor, 2010). Nevertheless, the selection of materials (Akadiri et al., 2013) remains extremely important in terms of sustainability. In addition, sustainable project management includes carrying out projects as efficiently as possible in order to minimise waste. Waste can be unnecessary transport or overproduction, but also idle resources or waiting times (Maltzman & Shirley, 2013). Both idle resources and waiting times relate to planning and sequencing projects (Silvius & Schipper, 2014a).

Risk management The final impact area of sustainability on the practices of project management that we will discuss is risk management. In project management, risk management (Office of the Government Commerce, 2010) is already extremely important because uncertain events or a series of uncertain events can strongly affect the overall performance and objectives of a project. The identification of potential risks is not an evident task, but financial risks, risks related to nature and its resources, social and socio-economic risks will certainly be considered (Chawla et al., 2018; Silvius & Schipper, 2014a). Makui et al. (2010) and Winnall (2013) strongly recommend identifying, analysing and adequately addressing uncertainties in advance rather than resolving them afterwards. The assessment of uncertainties and risks in project management events is possible through the prior estimation and evaluation of opportunities and threats and their potential impact on the overall achievement of objectives (Chawla et al., 2018). In essence, uncertainty and risk management are vital for sustainable project management (Turner, 2016). Efficient and effective uncertainty and risk management approaches and decisions ensure the achievement of sustainable project objectives combined with other benefits such as reduced investment in resources (Chawla et al., 2018; Turner, 2016).

In short, we find that integrating sustainability into project management can have an impact in several areas. The question of who is responsible for making this happen is a crucial one that arises. Several authors (Goedknegt, 2013; Hwang & Ng, 2013; Magano et al., 2021; Maltzman & Shirley, 2013; Silvius, 2016) highlight the role of project managers in the sustainable management of a project, as their central position offers many opportunities to influence the project. However, Silvius & Schipper (2014b) note that project management standards fail to reflect upon the role project managers play in achieving sustainable development. Moreover, they find that project managers lack the competences to integrate the sustainability aspects into their projects. Consequently, it is essential that the standards for project management competences (Silvius et al., 2012; Silvius & Schipper, 2014b) are updated to reflect the current required competences, including those related to sustainability.

In conclusion, research and initiatives are already ongoing to integrate sustainability into project management. In addition, researchers are addressing who should take primary responsibility for this and what areas sustainability will impact on. However, to assess sustainability at the project or organisational level, further research is needed to develop tools, techniques and methodologies (El-Haram et al., 2007; Martens & Carvalho, 2017; Singh et al., 2012; Thomson et al., 2011) that can be applied in project management. This is the need that we are addressing in this thesis, where we will focus mainly on the environmental impact. Moreover, we limit ourselves to construction projects, as the construction sector has enormous potential to contribute towards a more sustainable world. In the next section, we will briefly discuss the importance of sustainable integration in construction project management in particular.

1.3.1 Implementing sustainability in construction projects

After this explanation of how sustainable development can be applied in project management, we will complete our story and close the loop. We can no longer isolate the three fields of 'sustainability or sustainable development', 'project management' and the 'construction sector'. The three are inseparable, as shown in Figure 1.2. The environmental impact of the construction sector should not be underestimated. As mentioned in the introduction of this thesis, the construction sector is an enormous contributor to global greenhouse gas emissions, energy consumption and waste generation.

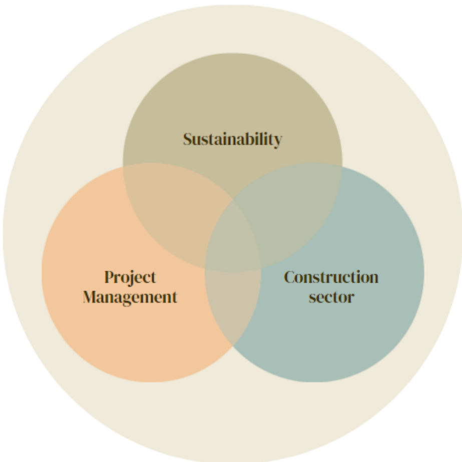


Figure 1.2: Interconnectivity sustainability - project management - construction sector

To counter such high-impact global problems, concrete actions are needed now. Circular construction can contribute towards achieving environmental goals. By using fewer materials, generating less waste and addressing vacancy among other things, the construction sector is contributing to the sustainable future (Benachio et al., 2020; VITO, nd). In order to implement sustainability in the construction sector (Benachio et al., 2020; Ghaffar et al., 2020; VITO, nd), it is crucial to consider the entire building process, from designing to demolishing. From the initial decisions, in the design phase, it is already important to prioritise long-term thinking and take into account what may happen to the building and its materials at the end of its life. This includes options such as layered design, where prefabricated modules provide flexibility, or design for reuse, where opportunities to mine materials from waste or residual streams are considered.

In essence, sustainable construction encompasses a wide range of strategies, including energy-efficient building design, selecting green materials, efficient use of water resources, waste management and recycling and engaging with the community. Sustainable construction (Hussin et al., 2013; Shen et al., 2010) can significantly reduce environmental impact, promote social well-being and contribute to long-term economic sustainability. Integrating such strategies into (construction) project management requires sustainability indicators that can be used to assess and monitor the environmental, social and economic performance of construction projects. Several studies (Fernández-Sánchez & Rodríguez-López, 2010; Stanitsas et al., 2021; Stanitsas & Kirytopoulos, 2023; Ugwu & Haupt, 2007) have already identified sustainability indicators to be integrated into project management practices. The sustainability indicators identified by Ugwu & Haupt (2007) and Stanitsas et al. (2021) include all three pillars of TBL, namely the economic, environmental and social pillar. However, their studies highlighted the need for more empirical research on sustainable project management indicators in construction projects.

Defining a widely accepted set of sustainable project management indicators can contribute towards the development of structured methodologies, techniques and decision-support tools by which designers and project managers can evaluate the sustainability of design proposals. To date, the research carried out in this area is rather limited. According to Robichaud & Anantatmula (2010), specific adaptations to traditional project management practices are needed with respect to the entire project management life cycle. The adaptations they propose to pursue a green building project emphasise early involvement of the entire project team and the provision of training and communication throughout the construction project. In addition, they suggest setting specific sustainability goals and project priorities well in advance, and including bonuses and rewards in project contracts to encourage the implementation of sustainable practices in construction projects.

The findings of Robichaud & Anantatmula (2010) are confirmed by the study of Verma et al. (2021): there are significant differences between standard and green building projects. Recognising these differences is crucial to developing frameworks and tools that support circular and sustainable construction. Verma et al. (2021) identified challenges such as higher project costs and the need for more and more detailed communication between project team members. In addition, they identified a lack of credible research on the benefits of green buildings and a lack of interest from clients.

In conclusion, further research is needed on the integration of sustainability into project management practices, especially in the construction sector. We can already argue that integrating sustainability into project management practices is having a significant impact. It has implications for project team composition and communication, project planning and scheduling, critical success factors, project control and many other areas. Moreover, there are many opportunities to make construction projects more sustainable. The use of green technologies is one of them, which we will explore in more detail in the next chapter.

2

Categories of Green Technologies

As the growing concern and severity of sustainability threats such as climate change and resource depletion, the need for sustainable project management practices becomes more and more apparent. Including environmental impacts in project planning and execution has become crucial for responsible project management. For this thesis, the financial and social aspects are out of scope, but this is also important to consider when choosing a green technology. The adoption of green and renewable technologies has emerged as a critical aspect of sustainable project management. These technologies can help reduce carbon emissions, enhance energy efficiency, and promote sustainable development. However, it is important to emphasise that green and renewable technologies are only part of the story of responsible construction project management or sustainable development in general. Considering only the environmental side, even in the construction industry alone, there are many actions to address environmental problems. Hence, much attention is paid to the use and reuse of resources or materials, energy-efficient building design, the use phase, waste management practices, and so on.

However, since there is a very intimate relationship between renewable energy and sustainable development (Omer, 2008a), we decided to focus in this thesis on three technologies that use renewable energy. Solar, wind and geothermal energy technologies will be discussed in depth, including environmental considerations. Moreover, for each category of technologies, we will subdivide it into subcategories that are distinguished by some important characteristics. This subclassification is valuable in identifying the similarities and differences between each other. Additionally, we will briefly explain technologies that rely on hydropower and biomass, among others, and refer to interesting review studies for a more thorough discussion.

By understanding the potential environmental benefits and challenges associated with the adoption of these technologies, project managers/teams can make informed decisions to enhance their sustainability efforts. A visual overview of some general environmental characteristics of solar, wind and geothermal technologies is presented in Table 2.1. The colour codes visually indicate which characteristics are favourable (green), less favourable (orange) or unfavourable (red) for the three technologies discussed. These technologies and their associated characteristics are discussed in more detail in the following sections. It is important to note that this overview is not exhaustive, as the categorisation of green technologies is not the focus of this thesis, but this can be further elaborated in subsequent papers.

	Emissions during use	Intermittency	Required land area	Water use	Noise pollution	Polluting production process of technology
Solar	None	Yes	Much	No	No	Yes
Wind	None	Yes	Little	No	Little	Yes
Geothermal	Little	No	Little	Little	Little	Yes

Table 2.1: General environmental characteristics of the three categories of technologies under investigation

2.1 Solar

The sun (Sample, 2008) is an interesting resource to generate electricity as it is free and inexhaustible. Additionally, solar energy technologies (SETs) are a very interesting avenue in times when we are trying to reduce carbon emissions as much as possible. A big advantage of SETs (Tsoutsos et al., 2005; Turkenburg et al., 2000) is related to the reduced CO_2 emissions and, normally, absence of any air emissions or waste products during their operation. However, we must take into account that some emissions (Tsoutsos et al., 2005) do arise from other phases of their life cycle, like during materials processing and manufacturing. The choice of these materials and the corresponding production process is evidently extremely important in determining the environmental impact of these technologies over their entire life cycle. In addition, there are other factors that are of great importance for the environmental impact (Tawalbeh et al., 2021): the production of hazardous contaminates, water resources pollution, the impact on land use and so on.

To find out typical characteristics of solar technologies (Goldemberg et al., 2000) we divide them into passive and active solar technologies. **Passive** technologies (Kabir et al., 2018) involve the accumulation of solar energy without transforming thermal or light energy into any other form. The application of passive solar principles can contribute significantly to the reduction of energy demands for heating, cooling, lighting and ventilating buildings (Goldemberg et al., 2000). This can be done through considering the solar geometry, window technology and local climate (Chel & Kaushik, 2018).

Active solar systems (Kabir et al., 2018) collect solar radiation and uses mechanical and electrical equipment for the conversion of solar energy to heat and electric power. In general, active solar energy technologies (Kabir et al., 2018) can be further grouped into two categories: (i) photovoltaic (PV) technology and (ii) solar thermal (ST) technology. The former (Baljit et al., 2016; Belyakov, 2019a; Parida et al., 2011) can be defined as the direct conversion of sunlight into electricity without any heat engine to interfere, whereas the solar thermal technology (Baljit et al., 2016; Belyakov, 2019a; Jamar et al., 2016) collects and concentrates solar energy by special devices after which solar radiation is converted into heat and transmitted into a transfer medium such as water antifreeze or air. In other words, PV technologies convert solar energy into useful heat whereas ST technologies convert solar energy into electrical energy.

2.1.1 Photovoltaic

Photovoltaic (NREL, nd) derives its name from the process of converting light (photons) into electricity (voltage), known as the photovoltaic effect. Photovoltaic technologies (Myers, 2012) utilise various semiconductor materials that release electrons from their constituent atomic structure that become available for conduction, or for the production of electric current. These technologies (Parida et al., 2011) has certain advantages such as they require very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts. Partly because of this, these technologies (Turkenburg et al., 2000) can be used in a wide variety of applications: from consumer products and small standalone units for rural use to grid-connected rooftop systems and large power systems. PV modules do not contain moving or rotating parts, hence, there is no significant noise pollution produced during their operation (Tawalbeh et al., 2021). Furthermore, this technology has the advantage of generating no chemical pollutants during use (Tsoutsos et al., 2005). In the summer, they are extremely efficient and they won't freeze over during the winter months (The Renewable Energy Hub, nd). Compared to solar thermal technology, PV technologies have an incredibly long lifespan (The Renewable Energy Hub, nd).

Unfortunately, there are also disadvantages associated with this subcategory. There are large areas required to capture the sunlight and there is a reduction of the cultivable land (Tsoutsos et al., 2005). Compared to solar thermal technologies, there is a lot more space needed for installation of PV systems (The Renewable Energy Hub, nd). As a comparison, a PV system could take up to 10m^2 of roof space as opposed to just 3m^2-4m^2 for a solar thermal system, which is due to its high efficiency (Lightsource bp, nd). As mentioned above, PV systems do not emit any gaseous, liquid or radioactive pollutants during their normal operation. In some cases, there is a potentially small risk that a fire in an array of a module could result in small amounts of these chemicals being released into the environment (Tsoutsos et al., 2005).

The next drawback is certainly something that we should not overlook, namely the energy-intensive production of photovoltaic systems (Tsoutsos et al., 2005). Depending on the modules and films used, small amounts of scarce, or even toxic, materials are often required (Tsoutsos et al., 2005). This is a subject of concern because on the long run the match between demand from the photovoltaics industry and the world market supply may become an issue at very large (mutiple gigawatts a year) production levels (Turkenburg et al., 2000).

It is also important to realise that, despite photovoltaic systems offering an intermittent source of energy, most standalone systems are equipped with battery storage (usually a lead-acid battery) to provide energy during night or during days with insufficient sunshine (Turkenburg et al., 2000). A life cycle analysis of batteries (Tsoutsos et al., 2005) for stand-alone PV systems indicates that the batteries are responsible for most of the environmental impacts, due to their relatively short life span and their heavy metal content. Furthermore a large amount of energy and raw materials are required for their production (Tsoutsos et al., 2005).

Another shortcoming is the efficiency of most domestic solar panels which are only around 10-20% (Kabir et al., 2018). However, more efficient (ca. >20%) solar panels are also available at higher prices (Kabir et al., 2018). The lower the efficiency, the higher the energy payback time. We can define this energy payback time (Asdrubali & Desideri, 2019; Frischknecht et al., 2016; Fthenakis & Raugei, 2017) as "the required period during which the PV system can generate the same amount of electricity (in terms of equivalent primary energy) as the energy consumed throughout its entire life cycle (from production and operation to end of life)". This is an important metric when calculating the environmental impact of solar energy technologies.

As described above, not everything is beneficial, as PV systems also have adverse elements that exacerbate the environmental impact. Certain opportunities do exist to mitigate these adverse effects. For example, Mozer & Sariciftci (2006) have been researching new materials for PV systems. It is important to minimise the use of hazardous materials and to think about recycling possibilities in advance. Other opportunities to substantially mitigate adverse effects (Tawalbeh et al., 2021) include optimised design and careful site selection. In the next section, we will discuss solar thermal technologies. Similar to photovoltaic technologies, these belong to the category of active solar energy systems.

2.1.2 Solar thermal

Solar thermal technologies (Asif, 2017) convert solar radiation into heat that either can be directly utilised for various applications or can be transformed into electricity to serve any purpose as deemed from conventional electricity. Basically, it differs from the previous category 'photovoltaic' in that the heat may be stored, commonly through using molten salts or oil as the liquid medium in the solar receiver, allowing electricity to be generated outside of sunlight hours. This category includes various technologies (Asif, 2017; Thirugnanasambandam et al., 2010) such as solar space heating, solar water heating, solar power plants (like CSP), solar conditioning, solar stills, solar chimneys, solar drying, solar cooking, solar architecture and solar ponds. These technologies can be further categorised as subcategories of solar thermal, but this is beyond the scope of this thesis.

Like photovoltaic systems, solar thermal systems also have some interesting advantages with respect to the environment. First of all, ST systems can store thermal energy since it directly produces heat (Danowitz, 2010). In addition, solar thermal offers the ability to match increased supply during periods of intense summer radiation with peak demand associated with space cooling requirements (Bahadori & Nwaoha, 2013). Secondly, solar thermal technologies are more space efficient than its solar PV counterpart (The Renewable Energy Hub, nd). Even more, ST electric systems are amongst the most efficient SETs when it comes to land use (they produce annually about 4–5 GWh/ha) (Tsoutsos et al., 2005). Thirdly, we would like to emphasise the importance of ST heating systems (Kicker et al., 2018). According to the research of Meyers et al. (2017), solar thermal heating systems will remain the preferred choice in most climates for lower temperature applications compared to photovoltaic heating systems. ST technologies can be employed to fulfil a considerable portion of heat demand in several industrial sectors (Allouhi et al., 2017). These were the main advantages of ST technologies.

Unfortunately, there are also some drawbacks. As we know there is significantly less sunlight during the winter months, especially during shorter days or when the sky is very cloudy. This is very disadvantageous for solar thermal systems since it affects the efficiency a lot. However, since ST systems are less sensitive to sunlight compared to PV, solar thermal will provide more return in cloudy weather than PV does (Bouquet, 2015; SolarShare, 2021). The second drawback that we discuss here is related to water resources. Solar thermal electricity systems (Tsoutsos et al., 2005) such as parabolic trough and central tower systems using conventional steam plant to generate electricity require the use of cooling water. This could place a significant strain on water resources in arid areas (Tsoutsos et al., 2005). In addition, there may be some pollution of water resources, through thermal discharges and accidental release of plant chemicals (Tsoutsos et al., 2005). In contrast, stand-alone parabolic dish systems (Tsoutsos et al., 2005) do not require water, except for periodic cleaning of the reflective surfaces, and therefore have little impact on water resources. Finally, we can state that solar PV systems tend to be a lot more versatile than the solar thermal systems and the lifespan of solar panels is larger compared to those of ST technology (McCloy, 2019; The Renewable Energy Hub, nd).

In addition to these characteristic features of solar thermal technologies, it is also useful to compare both categories. Based on the energy and exergy analyses of the photovoltaic, solar thermal and photovoltaic/thermal systems of Qingyang et al. (2020), it can be concluded that while the energy efficiency of the ST system is significantly higher compared to the PV system, the opposite is valid for the exergy efficiency. Compared with photovoltaic or solar thermal system alone, the hybrid photovoltaic/thermal system (Qingyang et al., 2020) has many advantages such as simultaneous production of electrical and thermal energies, efficient utilisation on solar energy, space reduction and so on.

In the table below, we summarise the categories of SETs discussed above and present their specific characteristics that distinguish them from any other category.

Subcategory 1	Subcategory 2	Heating of a fluid	Electricity production	Emission (during operation)	Direct conversion of electricity
Passive			x	x	
Active			v	x	
	Photovoltaics	x	v	x	v
	Solar thermal	v	v	x	x

Table 2.2: Characteristic properties of the different solar technologies

2.1.3 Environmental considerations

There are also a number of general characteristics that contribute to the environmental score of the respective solar energy technologies. First of all, Solar Energy Technologies (Bahadori & Nwaoha, 2013) do not deplete **natural resources**, produce CO_2 or other gaseous **emissions** into the air, or generate liquid or solid **waste products**. The second characteristic that we discuss here is about the **intermittency** of solar energy: solar generators only produce when the sun is shining (Gowrisankaran et al., 2016). This necessitates major energy storage as these sources increase their share of total energy supply (Moriarty & Honnery, 2016). A third concern is regarded to the **end-of-life recycling**. When the useful life of SETs such as solar panels is over, they become a form of hazardous waste (Xu et al., 2018). Moreover, recycling (ClearWorld, 2022; Panayotova & Panayotov, 2012) is one of the main ways to secure rare metals needed for new productions. Furthermore, recycling also leads to the **recovery of silicon**, which is by far the most common semiconductor material used in solar cells (Office of Energy Efficiency & Renewable Energy, nd). This is very beneficial since the energy and cost needed to recover silicon from recycled solar panels are equivalent to only one third of those of manufacturing silicon directly (Xu et al., 2018). We can conclude that recovering and recycling waste solar panels can reduce energy waste and environmental pollution (Xu et al., 2018), which is very interesting to include in the calculation of the environmental impact score of this technology. Since current recycling methods can recover just a portion the materials (Zaidi, 2018), there is plenty of room for progress in this area. Another important factor that has a major impact on the environmental performance of solar energy systems is the **energy efficiency** of the system manufacturing and electricity production in particular. The emissions (Tsoutsos et al., 2005) associated with transport of the modules are insignificant in comparison with those associated with their manufacturing. These following characteristics (Bahadori & Nwaoha, 2013) are also typical for SETs (with regard to their environmental impact): reclamation of degraded land, reduction of transmission lines from electricity grids, improvement of quality of water resources, increase of regional/national energy independence and diversification and security of energy supply.

The above characteristics are important elements that must be taken into account when calculating the environmental score of SETs. In the next section, we move on to wind technologies, where we also divide them into different categories and discuss some general environmental considerations.

2.2 Wind

Wind energy (El Bassam, 2021), which is produced by wind power, refers to the process of creating electricity using the wind, or air flows that occur naturally in the Earth's atmosphere. There are different wind energy systems (Kumar et al., 2016) that collect and convert wind energy into a useful form. A windmill converts the energy in the wind into electrical energy or mechanical energy to pump water or grind grain, whereas modern and commonly used wind turbines use the kinetic energy to generate electricity (El Bassam, 2021; Jacobson, 2009). In what follows, we will distinguish between vertical-axis wind turbines (VAWTs) and horizontal-axis wind turbines (HAWTs) on the one hand and between onshore and offshore wind turbines on the other. Afterwards, we will discuss some generic characteristics related to the environmental impact of technologies using wind energy.

2.2.1 Vertical-axis wind turbines vs horizontal-axis wind turbines

We can distinguish two categories of wind turbines in use today. There are vertical-axis wind turbines which, as the name implies, have a vertically oriented rotational axis and these can generally be driven by a lifting or dragging force (Belyakov, 2019b). The lift driven wind turbine is called the Darrieus type and the drag driven wind turbine is called the Savonius type (Kumara et al., 2017). The key advantage of this type of wind turbines, especially at sites where the wind direction is highly variable, is the fact that the turbine does not need to be pointed into the wind to be effective (El Bassam, 2021). Due to the fact that VAWTs are omnidirectional, they can be built closer to the ground, making them less susceptible to metal fatigue, highly space efficient and easily accessible (Nagare et al., 2015). In addition, VAWTs can generate power in weak and unstable winds, and these turbines generally produce little noise (Ahmad et al., 2022; Kumara et al., 2017). In contrast, VAWTs have a number of disadvantages (Beig & Muyeen, 2016; El Bassam, 2021) such as the low tip speed ratio and power output compared to horizontal axis generators, the inability to control power by pitching the rotor blades, and the required support or guy wires next to the tower.

In addition to the VAWTs, there are also horizontal-axis wind turbines. These are characterised by the fact that the axis of rotation is parallel to the ground (Belyakov, 2019b). These turbines have the main rotor shaft and electrical generator at the top of a tower and must be pointed into the wind (El Bassam, 2021). When the wind direction changes, the turbine again searches for the optimal position in relation to the wind (Cace, 2010). Small turbines are pointed by a simple wind vane, whereas large turbines generally use a wind sensor coupled with a computer-controlled motors (El Bassam, 2021). The major advantage of the horizontal type wind turbine is that by using blade pitch control, the rotor speed and power output can be controlled (Beig & Muyeen, 2016).

What is most commonly used today are the three blade horizontal axis wind turbines, with the turbine and its generator sitting on top of a tall tower (Breeze, 2021). These have certain advantages like high tip speeds of over 320 km/h (200 mph), high efficiency, and low torque ripple, which contribute to good reliability (El Bassam, 2021).

2.2.2 Onshore vs offshore

Wind turbines can be placed together onshore or offshore. There are some important differences between these two. An important difference between the two is the size, with offshore turbines being significantly larger than their onshore counterparts (Breeze, 2021). This is largely due to the transport of the very large turbine components, which is easier by sea than by land (Breeze, 2021).

Offshore wind farms are considered more efficient because of the higher wind speed, the greater consistency and the more abundant offshore wind compared to onshore wind (Bilgili et al., 2011; Liang & Feng, 2015). The higher wind speeds and better wind conditions enable offshore turbines to produce more electricity (Wagner et al., 2011). We can therefore conclude that, in general, the capacity factors are higher for offshore than for onshore and nearshore locations (Bilgili et al., 2011; Breeze, 2021; Soares-Ramos et al., 2020). In addition, the lower turbulence offshore results in reduced fatigue loads on the turbines (Milborrow, 2002).

As final advantage, we can mention that the visual impact and noise are almost negligible due to the remoteness of offshore wind turbines from the shore and the associated population (Bilgili et al., 2011; Soares-Ramos et al., 2020). Ideally, the offshore wind farms are far enough away to reduce visual and sound effects, but relatively close to coastal cities so that shorter transmission lines can be used (Bilgili et al., 2011). Since onshore wind farms are often located in remote areas, they also require relatively long power lines to transport electricity (Bilgili et al., 2011).

Based on these advantages, it is clear that offshore wind power (Liang & Feng, 2015) is very attractive due to the minimal environmental effect, which we focus on in this thesis. Of course there are also a number of disadvantages/challenges associated with offshore wind power. Due to the greater material input required, energy consumption and emissions (Wagner et al., 2011) are higher in the production phase compared to the onshore counterpart. The main energy intensive components are the offshore foundations and the submarine cables for the connection to the grid (Soares-Ramos et al., 2020; Wagner et al., 2011).

The installation, operation and maintenance of offshore wind turbines (Bilgili et al., 2011; Soares-Ramos et al., 2020; Wagner et al., 2011) can be considerably more expensive due to the great distance from the coast, the more complex maintenance procedures, the limited access to the sea and the weather conditions.

In the following, we will discuss in more detail the differences between VAWTs and HAWTs on the one hand, and between onshore and offshore wind turbines on the other. Our main focus will be on their energy efficiency and emissions.

Comparative analysis of technologies

The energy and greenhouse gas payback periods for wind turbines are generally less than one year, but these metrics vary for the different wind turbines (Guezuraga et al., 2012; Haapala & Prempreeda, 2014; Wagner et al., 2011). The vertical-axis wind turbines are both energy and emission intensive compared to the horizontal-axis wind turbines (Uddin & Kumar, 2014). The CO_2 emission intensity, which is the ratio of CO_2 emission to the electricity generation over the lifetime of wind turbine, is thus worse for VAWTS compared to HAWTS (Uddin & Kumar, 2014). This can be explained by the lower annual electricity generation of VAWTS (Uddin & Kumar, 2014). If we were to compare HAWTs and VAWTs based on unit electricity generation, the VAWT appears to be more environment friendly because of, among other things, the lower weight, simpler foundation and less maintenance costs (Rashedi et al., 2013).

Conclusions based on the energy payback time between different technologies are valuable and can be a determining factor in the selection of a particular technology. However, it is difficult to give exact values for this metric as it depends on the specific properties of the wind turbines, the country energy mix, the other assumptions made, etc. Moreover, the location of the wind turbine also has a major influence on this. Typically, it takes a little longer for the energy use of offshore wind farms to be paid back compared to the onshore ones (Schleisner, 2000). Also with regard to life cycle greenhouse gas emissions (Wang et al., 2019), offshore wind turbines score worse than onshore wind turbines. The SO_2 emissions per kWh and the NO_X emissions per kWh are broadly similar for both (slightly higher for offshore), but the CO_2 emissions per kWh for offshore wind farms are quite a bit higher compared to those on land (Schleisner, 2000). The life cycle greenhouse gas emission intensity of both onshore and offshore wind farms is still much smaller than coal power plants (Wang et al., 2019). The overall impact of offshore plants, compared to onshore ones, is higher which is largely due to the greater high-impact material requirements for capital infrastructure (Bonou et al., 2016). These material and energy requirements do not counterbalance the benefits of higher energy output compared to the onshore market (Bonou et al., 2016).

Based on the life cycle assessment of two different 2 MW class turbines, investigated by Guezuraga et al. (2012), we have gained some more interesting insights. The main impacts on the energy requirements throughout the turbine's life (Guezuraga et al., 2012) originate from the manufacturing phase (84%) and the transport (7%). The turbine is clearly the most energy intensive component of wind turbine systems (Uddin & Kumar, 2014). We also want to emphasise the importance of recycling (Uddin & Kumar, 2014). Even though the disposal scenario (Guezuraga et al., 2012) represents only 3.1% of the total energy demand, it is extremely important to recycle materials. Without recycling, the energy requirement and the CO_2 emissions (Guezuraga et al., 2012) both increase by more than 40%. Recycling of wind turbines (Jensen, 2019) also offers other significant environmental benefits such as reducing the use of natural resources. Finally, we compare the energy payback time with a nuclear and a coal fire power station, which is respectively 3.16 and 2.72 times longer compared to that of wind power (Guezuraga et al., 2012). Hydropower, on the other hand, has a slightly smaller environmental impact than wind energy, according to the study by Guezuraga et al. (2012). Some more general environmental considerations for which wind turbines are known are discussed below.

2.2.3 Environmental considerations

As with each category, we will also discuss some of the factors that influence the environmental impact of wind energy technologies. We start by discussing three advantageous aspects and proceed to some disadvantages or challenges associated with wind energy technologies.

As with the previous category (solar), wind energy (Beig & Muyeen, 2016; Wagner & Mathur, 2018; Zahedi, 2012) also has the advantage that no fossil fuels are burned to generate electricity from wind, meaning that wind turbines produce **no harmful emissions**. During the construction of wind turbines, most of the greenhouse gases come from the production of concrete and steel for the foundation (Wang & Wang, 2015). This is important if we take the entire life cycle of wind turbines into account when calculating the environmental impact. According to Jacobson (2009), wind turbines have one of the lowest life-cycle CO_2 equivalent emissions, ranging from 2.8g to 7.4g per kWh of electricity generated. Depending on the size of the wind farm, the methods used to estimate greenhouse gas emissions from the wind farm's life cycle and the locations, the range can still rise to 86 g CO_2 emissions per kWh (Wang & Wang, 2015).

Secondly, wind turbines can be placed in **remote locations**. Where conventional power lines cannot be extended due to environmental and economic considerations, wind energy is a suitable option as a small local electricity grid can be used instead of connecting to a large-scale electricity grid (Beig & Muyeen, 2016; Zahedi, 2012). In addition, wind energy can be used for a wide variety of applications. On the one hand wind energy (Zahedi, 2012; Musgrove, 1987) can be used for kilowatt-scale systems needed for water pumps, rural electricity and telecommunications, but on the other hand, wind farms can also be made on large scale for providing electricity to national utility systems. Moreover, wind energy (Beig & Muyeen, 2016; Wagner & Mathur, 2018) also has the advantage that the necessary space is limited, which means that land owners can still use a large part of their field.

The third advantage relates to **water resources** (He et al., 2021), which can certainly be important with increasing water scarcity as time goes on. Compared to conventional power plants or technologies using solar, thermal or biomass energy, a wind power plant (Saidur et al., 2011) consumes very limited water resources, approximately 0.004 litres per kWh of electricity generated.

By discussing these benefits of wind energy, the potential is clear. Unfortunately, there are also some disadvantages or challenges associated with wind power that we discuss below.

First of all, wind power generation has **intermittent nature** (Rahimi et al., 2013) which means that the power generated is a function of wind speed. This is a very challenging problem for technologies based on wind power. Wind power is very variable and unpredictable (Breeze, 2021). When the wind speed is too low to support a wind turbine, little electricity is generated (Beig & Muyeen, 2016). The intermittent nature of wind (Rahimi et al., 2013) also leads to technical problems such as generation imbalance as well as optimal reserve allocation. Unfortunately, the ability to store energy is limited (Belyakov, 2019b).

Second, we mention the **impact on wildlife**. This can be done directly, such as fatal accidents of birds, for example, and indirectly, such as loss of functional habitat or barriers to movement (Belyakov, 2019b).

The third drawback we discuss is **shortage of rare earth elements**. The global expansion of wind power raises concerns about the shortage of some rare earth elements (Li et al., 2020), such as neodymium, praseodymium, and dysprosium, which are required for the production of permanent magnet electrical generators.

Furthermore, we would like to mention two disadvantages of wind energy, although we would like to say that these are perceived as rather small. Wind turbines cause **noise pollution** in the form of both mechanical and aerodynamic noise (Wang & Wang, 2015). The former is generated by the turbine's mechanical and electrical parts, while the aerodynamic noise is generated by the interaction of blades with the air (Wang & Wang, 2015). The last disadvantage is about the **visual appearance and disturbance of landscape**. People can complain about, for example, oscillation shadow due to rotating blades (Belyakov, 2019b).

We have already discussed the categories of solar and wind technologies. These technologies had some similar environmental characteristics, such as no emissions during operation and the challenge of recycling. In the next section we will cover technologies using geothermal energy. Similarly, we will discuss some key environmental considerations for this category of technologies.

2.3 Geothermal energy

Geothermal energy (Breeze, 2021; Fridleifsson, 1998) harness the heat from the Earth to generate electricity or heat for a variety of purposes. The origin of this heat is linked to the internal structure of our planet and the physical processes taking place there (Stober & Bucher, 2021b), causing 99% of the Earth to be hotter than 1000°C and only 0.1% to be colder than 100°C. The core itself is extremely hot, and this heat slowly radiates to the surface, causing substrata of our planet to be warmer than the surface (Breeze, 2021). This may sound extremely interesting, especially when considering the enormous, practically inexhaustible quantities of this heat present in the Earth's crust and certainly in the deeper parts of our planet. Unfortunately, the heat is unevenly distributed, rarely concentrated, and often at depths too deep to be exploited industrially (Barbier, 2002).

Technologies exploiting geothermal energy (Kulasekara & Seynulabdeen, 2019; Moya et al., 2018) appear to have tremendous potential to reduce environmental impact and greenhouse gas emissions. There are two main ways that geothermal resources are used for energy applications (Avci et al., 2020; Bertani, 2009; van der Zwaan & Dalla Longa, 2019): either through the generation of electricity or through various 'direct use' thermal applications including space heating and industrial heating.

In 2021, the installed electricity capacity of geothermal energy (Geothermal Energy Association, 2009; Huttrer, 2021; IRENA, 2022; Jaganmohan, 2022; Richter, 2022; Salhein et al., 2022; Sharmin et al., 2023; Our World in Data, 2021) was 15.64 gigawatts electrical (GW_e), of which 95% was generated in 10 countries, namely (in descending order) the United States, Indonesia, the Philippines, Turkey, New Zealand, Mexico, Italy, Kenya, Iceland and Japan. The renowned academic researcher Bertani (2016) forecasts that the worldwide geothermal energy power generation installation capacity for 2025, 2030, and 2050 will be 19.10, 51, and 70 GW_e, respectively. These forecasts allow us to conclude that the percentage increase in world total installed capacity from 2010 to 2020 is not projected to the same extent in the years after 2020. The update report written by Huttrer (2021) on "Geothermal Power Generation in the World 2015-2020" highlights three reasons that may explain this outlook. A first reason would be the competition of plants powered by wind, solar and natural gas that have lower risks, shorter payout periods and lower cost per kWh. The reduced projected increase could also be attributed to the continued slow adoption of specific geothermal policies, laws, rules and regulations in some states. A final reason involves the bureaucratic delays required to gain access to the land, remove local ownership, environmental and other objections/barriers, obtain all required permits, and finally explore, develop, construct and commission all aspects of a geothermal field, power plant and transmission facilities. The latter can extend the time required to complete geothermal projects to several years compared to the one year or even several months typically required to build and operate wind and solar power plants.

For the installed thermal power for direct utilisation, Lund & Toth (2021) estimate 107.73 gigawatts thermal (GW_t) at the end of 2019. Also in terms of direct geothermal use, there were a few top countries that together accounted for about 75% of the global total, namely China, Turkey, Iceland and Japan (Avci et al., 2020). In most countries, however, development has been slow so far, but a strong growth is expected due to increasing research, development and technological innovation in this field (Lund et al., 2015; Lund & Toth, 2021).

Lund & Toth (2021) provide us with some recent global statistics to give us an idea of the scope of geothermal applications. For both direct use and electricity generation, a total of approximately 2647 wells were drilled in 42 countries. In the period 2015-2019, about $22.262 billion was invested by 53 countries in geothermal projects for both electricity (64%) and direct use (36%).

To explore the range of applications in more detail, we briefly review the Lindal diagram (Dickson & Fanelli, 2011; Kaczmarczyk et al., 2020; Matuszewska et al., 2020; Operacz & Józef, 2018) shown in Figure 2.1. However, the boundaries serve rather as guidelines (Fridleifsson, 1998). In addition, it is also important to emphasise that the temperature of the geothermal fluid is not the only parameter that determines the possibilities. Additional factors (Kaczmarczyk et al., 2020) to consider are the specific geological, hydrogeological and thermophysical conditions such as temperature, flow rate and mineralisation of geothermal water prevailing in the area to be analysed. Depending on the specific conditions, the possibilities can be determined. These vary from indirect use, such as electricity generation, to direct use of hot springs for bathing, aquaculture, geothermal heating, and so on (Matuszewska et al., 2020).

Similarly to how we subdivided solar and wind energy technologies in the previous sections, we will also categorise geothermal technologies to find typical environmental characteristics for each cluster. First we will discuss the geothermal power plant technologies and subsequently we will elaborate on the direct use of geothermal energy by ground source heat pump, among others.

2.3.1 Electricity generation

The dominant form of utilisation (Dickson & Fanelli, 2011; Lund et al., 2008) is electricity generation that requires high-temperature geothermal resources, typically higher than 150°C. To understand the various technologies that are classified under this category, it is important to have an understanding of how Earth's internal heat is converted into electricity. As

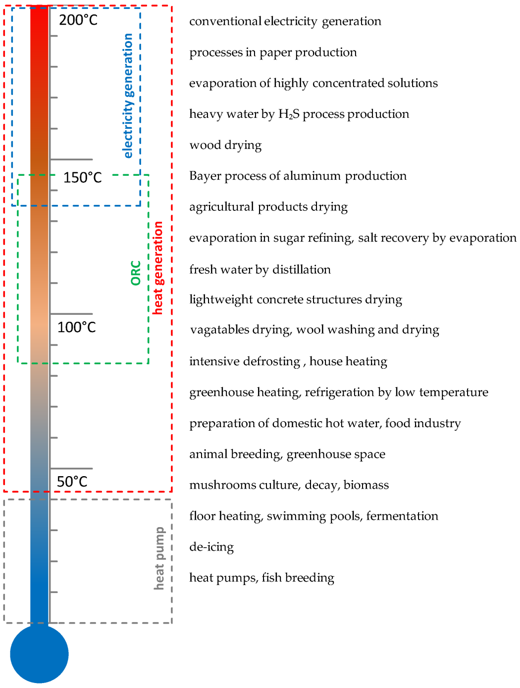


Figure 2.1: Modified Lindal diagram (Matuszewska et al., 2020)

a result of geological processes, such as plate tectonics, temperatures in the Earth's interior can rise high enough to melt rock and form magma (Rashid et al., 2012). Since magma is less dense than surrounding rock, it moves up into the Earth's crust (Kagel et al., 2005a). Through a thin or broken crust, magma can rise to the surface as lava. However, most magma remains below the Earth's crust and heats surrounding rocks and subterranean water, including water in rock pores and fractures (Kagel et al., 2005a). When this rising hot water and steam become trapped in permeable rocks under a layer of impermeable rocks, this is known as a geothermal reservoir (Rashid et al., 2012). These reservoirs are sources of geothermal energy that can potentially be tapped for electricity generation or direct use.

In the case of electricity generation, although the practices of different technologies may differ, the basic principle of geothermal power generation (Kulasekara & Seynulabdeen, 2019) is always based on the conversion of the Earth's internal thermal energy into electrical energy. Water or hydrothermal fluid is injected through injection wells to extract heat from the geothermal resource (Kulasekara & Seynulabdeen, 2019). The hot fluid is used to produce pressurised steam that is stroked onto turbine blades, converting thermal energy from the stream into the kinetic energy of the turbine (Kulasekara & Seynulabdeen, 2019). A generator coupled to the turbine converts the kinetic energy into electrical energy (Kulasekara & Seynulabdeen, 2019).

The technologies used for electricity generation from geothermal energy are called geothermal power plants. The selection of the most suitable technology for geothermal power generation depends mainly on the properties of geothermal resource (fluid and reservoir) to be exploited, meaning more specifically the geological, chemical, physical and thermodynamic properties (Gupta & Roy, 2007; Tomasini-Montenegro et al., 2017). According to Lund et al. (2008), we can classify geothermal resources suitable for power generation into three groups: vapour-dominated systems with temperatures > 240 °C, liquid (or hot water) dominated systems with temperatures up to 350 °C, and hot rock resources with temperatures up to 650 °C. We can classify the first two under convective hydrothermal resources which are commercially exploited in the world. In general, vapour or liquid dominated geothermal power plant technologies (Avci et al., 2020; Chamorro et al., 2012; Jacobson, 2009; Kulasekara & Seynulabdeen, 2019; Yari, 2010) that have been used commercially and successfully to exploit geothermal resources can be further classified into dry steam, flash steam and binary power plants.

Dry steam power plants

Dry steam power plants use hydrothermal fluids that are primarily steam. The steam from the hydrothermal reservoir goes directly to the turbine, which drives a generator that produces electricity as said before. A condenser is then used to liquefy the steam by reducing its temperature and afterwards the hydrothermal fluid is injected back into the reservoir through the injection well (Kulasekara & Seynulabdeen, 2019). Steam technology (EERE, nd; Ngala et al., 2015) is used today at The Geysers in northern California, the largest single source of geothermal power in the world. Another geothermal field that remains highly effective is that of Larderello in Italy, which incidentally was the first to be used (Moya et al., 2018; Ngala et al., 2015). Dry steam power plants (Ngala et al., 2015) emit only excess steam and very small amounts of greenhouse gases to the atmosphere. However, what can be very detrimental is the corrosion and erosion of the turbine blades due to the fact that these blades are in direct contact with the steam consisting of impurities (Ngala et al., 2015).

Flash steam power plants

The second type of geothermal power plant technology we will discuss is the flash steam power plant. Previously, we discussed how a vapour-dominated source (dry steam) could be used directly. In contrast, the more common hot water source must be flashed by reducing the pressure to produce steam (Chamorro et al., 2012; Lund et al., 2008). First, the highly pressurised hot water or hydrothermal fluid is drawn from the hydrothermal reservoir deep in the Earth and collected using a steam separator (Kulasekara & Seynulabdeen, 2019). The high-pressure hot water in the separator moves upwards by its own and the pressure decreases as it moves to the surface (Kulasekara & Seynulabdeen, 2019). Once the geofluid temperature reaches the corresponding saturation pressure, the fluid begins to boil or 'flash', creating a two-phase, liquid-vapour mixture (DiPippo & Renner, 2014). Since turbines generally require dry or superheated steam to prevent erosion and/or corrosion damage to the nozzles and blades, a separator segregates the mixture (DiPippo & Renner, 2014). The flashed steam actuates the turbine to drive the generator, and the liquid water is reinjected back into the reservoir (DiPippo & Renner, 2014).

Depending on the characteristics of the thermodynamic mixture, the separation process can involve one, two or three phases, namely single, double and triple flash technologies, respectively (Tomasini-Montenegro et al., 2017; Valdimarsson, 2011). The design of single flash plants can be improved if the liquid phase undergoes one additional flash processes to obtain more steam at a lower pressure (Chamorro et al., 2012). In practical terms, this means that remaining liquid phase (also known as brine) is again separated by a second separation stage (known as double-flash) that is added. The secondary low-pressure steam is directed to a low-pressure turbine or an appropriate stage of the flash plant, generating more power from the same geothermal reservoir than a single flash plant (Chamorro et al., 2012). In this regard, a third separation stage could be added, which would be called a triple-flash power plant.

Flashed steam plants are further characterised by the fact that they do not require a separate supply of cooling water for the condenser (DiPippo & Renner, 2014). Due to the thermodynamic properties of water, excess condensate is available from the cooling tower, which is usually reinjected (DiPippo & Renner, 2014). Between 80% and 85% of the geofluid extracted from the reservoir is available for reinjection (DiPippo & Renner, 2014). This implies that such plants can be used in geothermal fields where there is too little or no surface or groundwater (DiPippo & Renner, 2014). In comparison with dry steam plants, the percentage of produced fluid available for reinjection is relatively low, roughly 15% to 20%, compared with the 80% to 85% for flash steam plants (DiPippo & Renner, 2014). In contrast, dry steam plants are simpler, more efficient and economical, but unfortunately they are also rare (DiPippo & Renner, 2014).

Binary cycle power plants

The third one we discuss is binary cycle power plant (Chamorro et al., 2012; Paulillo et al., 2022) which is appropriate when the geofluid temperature in the geothermal reservoir is lower than 150 °C, where single and multistage flash plants are less efficient and consequently less economical. The heat energy of the hot geothermal fluid from the hydrothermal reservoir is transferred through a heat exchanger to a secondary (hence 'binary') fluid with a much lower boiling point than water (Kulasekara & Seynulabdeen, 2019; Ngala et al., 2015). As a result, the secondary fluid begins to vaporise, which in turn drives the turbines. The average capacity of these plants is about 6 MW per unit (Paulillo et al., 2022). However, units with higher capacities of about 20 MW are being developed through advanced binary cycle designs such as dual pressure, dual fluid and Kalina binary cycles (Paulillo et al., 2022).

A major advantage of the generic binary plant is the low required operating temperature of the primary hydrothermal fluid, since the secondary fluid has a lower boiling point (Ngala et al., 2015). In fact, geothermal binary plants are among the most environmentally friendly of all power plants (DiPippo, 2005). As a result of the design of binary cycle geothermal power plants, no greenhouse gases are emitted (DiPippo & Renner, 2014; Kulasekara & Seynulabdeen, 2019; Ngala et al., 2015; Paulillo et al., 2022). The biggest environmental threat is related to the loss of the working fluid (the secondary fluid), which can be a potent greenhouse gas, as in the case of refrigerants such as R32 or R134 (DiPippo, 2005; Paulillo et al., 2022). Nevertheless, injecting the produced fluid back into the geothermal system ensures that electricity production can be preserved even in fields with limited water resources (DiPippo & Renner, 2014). Unfortunately, unlike steam or flash plants, binary plants do require an external cooling source to condense the working fluid, since neither the geothermal brine nor the working fluid can be used as a cooling source (DiPippo & Renner, 2014).

Enhanced geothermal systems

To complete our story, we also include enhanced geothermal systems (EGS) in the geothermal power plant category. The previously reviewed power plants used hydrothermal resources (Eyerer et al., 2020), i.e. geothermal reservoirs of steam or hot water with naturally permeable aquifers. These hydrothermal reservoirs had to be located first, after which they could be investigated for their potential and then possibly exploited. Ultimately, at the current state of technology, there are few geothermal resources on Earth that have the potential for long-term exploitation because of their desirable characteristics, such as significant amounts of heat (and fluid), availability in non-volcanic areas and low permeability in their reservoirs (Huenges, 2016; Olasolo et al., 2016).

These limitations have forced scientists to explore alternative solutions (Wong & Tan, 2015) in order to preserve geothermal energy as a viable, functional energy source with a promising future. To reduce dependence on naturally occurring geothermal reservoirs, the creation of artificial flow paths in the more prevalent petrothermal reservoirs was proposed. This alternative is known as enhanced geothermal systems, which Huenges (2016) defines as " geothermal reservoirs enabled for economic utilisation of low permeability conductive rocks by creating fluid connectivity in initially low-permeability rocks through hydraulic, thermal, or chemical stimulation". In other words, these systems (Breede et al., 2013) are aimed at exploiting widely available deep underground reservoirs, where insufficient water is present and/or the permeability of the rock formation is low. To achieve this, pre-existing fractures and fracture systems are used by hydraulically increasing reservoir pressure to create artificial flow paths in an impermeable rock matrix (Loewer & Keim, 2022). The term 'enhanced geothermal system' refers both to the catalog of technical measures and to the geological system itself, whose low hydraulic permeability is artificially increased by these measures to make it geothermally usable (Loewer & Keim, 2022).

A global estimate of the potential of enhanced geothermal systems conducted by Aghahosseini & Breyer (2020) shows that the renewable potential of EGS in 2050 is 256 GW_e, giving EGS a noticeable potential to increase the share of renewable energy in the energy mix. However, there is still an urgent need for research in the field of geothermal energy, and in particular for petrothermal resources (Avci et al., 2020; Pan et al., 2019).

2.3.2 Direct utilisation

Direct utilisation of geothermal energy is one of the oldest, most versatile and most common form of utilising geothermal energy (Dickson & Fanelli, 2003). In this regard, the technologies directly use geothermal energy for heating, cooling and other applications without converting it to electricity. Lund & Toth (2021) divided the wide range of applications based on the distribution of thermal energy used by category: approximately 58.8% for geothermal (ground source) heat pumps, 18.0% for bathing and swimming (including balneology), 16.0% for space heating (of which 91.0% is for district heating), 3.5% for greenhouse heating, 1.6% for industrial applications, 1.3% for aquaculture pond and raceway heating, 0.4% for agricultural drying, 0.2% for snow melting and cooling, and 0.2% for other applications.

As illustrated in the Lindal diagram in Figure 2.1, the appropriate temperature of the geothermal energy resource varies for the different applications. In general, the temperatures of geothermal fluid required for direct use (Gudmundsson & Lund, 1985; Sircar et al., 2016) are lower than those for economic electricity generation. Direct-use projects can use geothermal resources with both low and intermediate temperatures (typically < 150°C), which are more widespread around the world than those for power generation (Fridleifsson, 1998; Omer, 2008b). Although direct heating has lower heat source temperature requirements, it is much more efficient than electricity generation (Avci et al., 2020).

The required heat can be extracted in various ways intended for thermal applications (Mburu, 2015). In the case of natural hot springs, the heated water can be pumped directly into radiators. The heat can also come from co-generation with a geothermal power plant or from smaller wells or heat exchangers in shallow ground. In the presence of warm but dry ground, earth tubes or downhole heat exchangers can capture the heat. Yet even in areas where the ground is colder than room temperature, it is possible to extract heat with a geothermal heat pump. This is even more cost-effective and cleaner compared to conventional furnaces (Lund, 2006).

Geothermal direct-utilisation systems (Lund, 2006; Lund et al., 2008) usually consist of the following components: downhole and circulation pumps, heat exchangers, transmission and distribution pipelines, heat extraction equipment, peaking or back-up plants and a fluid disposal system. A concern is the corrosion and scale that can be caused by the chemistry of geothermal fluids, which can cause operating problems with equipment components (Gunnlaugsson et al., 2014; Lund, 2006; Lund et al., 2008). Such problems can usually be solved or at least minimised by better design and operation of wells and the entire system, proper material selection and chemical treatment of geothermal fluids (Gunnlaugsson et al., 2014).

A rapidly emerging technology in terms of development and use with still enormous potential is the ground source heat pump (Sanner, 2017; Sircar et al., 2016). For both commercial and residential buildings, heat pumps (Omer, 2008b; Sarbu & Sebarchievici, 2014) offer the most energy-efficient way to provide heating as well as cooling and as a result contribute significantly to reducing CO_2 emissions. A typical ground source heat pump system (Sarbu & Sebarchievici, 2014; Self et al., 2013) mainly consists of three parts: a ground connection subsystem, heat pump subsystem, and heat distribution subsystem. Geothermal heat pumps include both open-loop systems that use surface or groundwater directly and closed-loop systems in horizontal or vertical configuration (Lund et al., 2008).

Recently, researchers (Asadi et al., 2022; Avci et al., 2020; Eyerer et al., 2020; Lund & Chiasson, 2007) have often investigated combined heat and power plants, which would significantly improve the overall efficiency of the geothermal utilisation. Additionally, there is strong interest in the development of hybrid power plants (Astolfi et al., 2011; Ayub et al., 2015; Peterseim et al., 2013, 2014a,b; Thain & DiPippo, 2015) that combine geothermal systems with biomass, waste-to-energy technologies, fuel cells or solar heating systems. In conclusion, there is certainly a lot of potential in the use of geothermal energy (Milousi et al., 2022) whether combined with other renewable energies or not.

2.3.3 Environmental considerations

Similar to how we covered the environmental considerations of solar and wind energy in the previous sections, we will now provide a similar discussion for geothermal energy. In the following, we will identify 13 aspects that affect the environmental impact of geothermal technologies.

First of all, we can emphasise that geothermal energy is considered **sustainable and reliable**, as it is available 24 hours a day regardless of weather conditions (Eliasson et al., 2014). The reliability, predictability and consistency is a major advantage as opposed to most other renewable sources such as solar and wind energy (Kulasekara & Seynulabdeen, 2019).

Furthermore, geothermal energy is also environmentally friendly. In general, we can state that the environmental impacts of geothermal energy generation and direct use are minor and, in most cases, even controllable (Dhar et al., 2020). The average **emissions** to the atmosphere are low, as well as the harmful environmental effects during normal operation and even during accidents (Brophy, 1997; EIA, 2022; Hanbury & Vasquez, 2018; Kagel et al., 2005b; Lukawski et al., 2018; Milousi et al., 2022; Moya et al., 2018; Stober & Bucher, 2021a).

Third, we can also argue that little **land area** is required to operate geothermal energy and they impose minimal **visual impact** on their surroundings (Bošnjaković et al., 2019; Dhar et al., 2020; Eliasson et al., 2014; Soltani et al., 2021). Moreover, geothermal power plants are often located on lands that serve multiple functions, including agriculture, skiing and hunting (Kagel et al., 2005b).

However, there are two **potential hazards associated with soil**, namely subsidence and induced seismicity (Dhar et al., 2020). *Soil subsidence*, or the slow downward sinking of land, can occur as a result of the extraction of subsurface fluids, including groundwater and geothermal fluids (Kagel et al., 2005b; Mossop & Segall, 1997). The reduced pore pressure in the geothermal reservoir causes less support of the reservoir rock itself and the rock above the reservoir. Consequently, this can lead to a slow, downward deformation of the land surface. However, this effect can be reduced by properly placed injection that maintains reservoir pressure (Allis et al., 2009). On the other hand, there is evidence that geothermal production and injection operations can result in the generation of earthquake activity, or *seismic activity* (Buijze et al., 2019; Giardini, 2009; Johnson, 2014; Soltani et al., 2021). However, these events are of low magnitude and typically cannot be detected by humans.

Fifth, there are also little to no adverse effects in terms of **noise pollution**. Nearby residents of geothermal systems may experience noise pollution during the construction stage of these systems due to excavation for drilling sites, drilling of wells and testing of wells (DiPippo, 2016). However, noise is not considered a concern during normal operation as it is very low. Most of the noise is caused by cooling fans and the rotating turbines (Soltani et al., 2021).

In terms of **water use**, the needs of geothermal projects are quite low. Speaking specifically of geothermal power plants, they require less water per unit of energy generated than coal, nuclear and natural gas (Clark et al., 2010; Soltani et al., 2021). The two most demanding areas in terms of water use are well drilling and waste heat disposal if a water cooling tower is used (DiPippo, 2016). Regarding water pollution, it would be harmful to humans, animals and plants if geothermal fluids may get into the environment (DiPippo, 2016). A suitable way to remove this fluid, without discharging it into surface effluent ponds, is to inject the geothermal fluid back into the ground (Stefansson, 1997). Reinjecting geothermal fluids used for electricity back into geothermal reservoirs reduces surface water pollution and increases the resilience of geothermal reservoirs (Kagel et al., 2005b; Mott et al., 2022).

Since the exploitation of geothermal resources may involve adverse effects to terrestrial, riparian and aquatic habitats, this is also worth discussing (Soltani et al., 2021). However, compared to alternatives such as coal or other energy sources, geothermal energy development has minimal **impact on wildlife** (Brophy, 1997; Kagel et al., 2005b). This is partly due to the design of geothermal systems in which pipes are insulated to prevent heat losses, power plants are fenced to prevent wildlife from entering, and areas with high concentrations of wildlife or vegetation specific to an area are avoided (Kagel et al., 2005b). Their construction even requires compliance with numerous state and federal regulations protecting development areas.

Additionally, we can also assume that the impact of **solids pollution** is negligible (DiPippo, 2016). This solid waste includes materials initially dissolved in the geothermal fluid (Soltani et al., 2021).

The ninth aspect is that geothermal power generation is generally very **cost-competitive** compared to conventional sources of energy (Barbier, 2002; Timilsina, 2021). However, the risk of investment in a geothermal technology is relatively high since the geothermal resource size and quality is unknown before drilling the well (Ciriaco et al., 2020). Besides the difficulty for resource assessment, these technologies also require a high initial investment, a long payback and construction time (Li et al., 2015; Soltani et al., 2021; Stefánsson, 2002). These reasons contribute to the slower growth and lower installed capacity of geothermal power relative to wind and solar power.

Although the previous paragraphs have been rather positive (except for the soil hazards), there are still some drawbacks to geothermal technologies that need to be considered. As mentioned earlier, **resource assessment** is a difficult task. Both finding a suitable site and investigating the resource requires a lot of time, effort and money (Mohtasham, 2015). Certain technologies already discussed exploit extremely scarce hydrothermal reservoirs. To counteract this geographical dependence, enhanced geothermal systems have been initiated that enhance and/or create their own geothermal resource. This technology is promising, but too little research has been done to assess it thoroughly (Aghahosseini & Breyer, 2020; Hanbury & Vasquez, 2018; Menberg et al., 2016; Rybach, 2010). Besides the scarcity of suitable sites and the difficulty of assessing them, there is also an issue of safety. On the one hand, the concentration of geothermal energy is typically located along plate boundaries, where volcanoes are concentrated and earthquakes are most common (Mohtasham, 2015; n.d., 2023). On the other hand, we have already discussed induced seismicity that is induced by geothermal energy extraction.

Another disadvantage of geothermal technologies, and power plants in particular, is the **lower efficiency** of power generation compared to other energy sources (Anderson & Rezaie, 2019; DiPippo, 2015). Nevertheless, it is an interesting possibility to combine geothermal resources with other energy sources to achieve higher efficiency.

The twelfth aspect covers the importance of considering **hazardous materials** from the subsurface that need to be dealt with (Mohtasham, 2015). These can include hydrogen sulphide, mercury, ammonia or arsenic.

Finally, we question whether geothermal power is **effectively renewable**. Energy is extracted from the Earth but is not replenished (Breeze, 2021). In practice, though, only a small amount of energy is extracted and therefore it has no effect on the temperature of the core.

Until now we have discussed technologies that use solar, wind or geothermal energy. For each category, we have discussed some of the environmental factors that are important in calculating the environmental impact score. In the next section we briefly discuss some other categories of technologies. For the interested reader who wants a more in-depth discussion, we refer to some interesting publications.

2.4 Other categories

We have already investigated some interesting renewable energy sources, but there are still interesting avenues to explore. Examples include hydropower, biomass, tides, waves etc. It is also interesting to compare renewables with other energy sources such as nuclear power or fossil energy (such as oil, coal and natural gas).

Although an analysis of renewable or non-renewable energy technologies that we have not yet discussed is very interesting, it is out of scope for this thesis. The book "Renewable Energy Sources and Climate Change Mitigation" (IPCC, 2011) is an interesting reference. This book covers bioenergy, solar, geothermal, hydropower, ocean and wind energy. The environmental and social impacts of implementing these technologies are also discussed in detail to ultimately evaluate the potential role of renewable energy in climate change mitigation. Some academic researchers (Breeze, 2021; Dincer, 2000; Jacobson, 2009; Mohtasham, 2015; Panwar et al., 2011; Sayed et al., 2021) have already written a review paper covering several green technologies based on renewable energy. Furthermore, analyses (Jin & Kim, 2018; Karakosta et al., 2013; Rahman et al., 2022) of these technologies can also guide us in a more profound qualitative analysis of their environmental impact.

Many authorities or cooperating organisations, such as the 'Renewable Energy Policy Network for the 21st Century' and the 'International Energy Agency', firmly believe in the potential of renewable energy and emphasise the crucial role for policymakers. Their influential publications go beyond environmental impact analysis to include the policy landscape around it and the impact of earth-shattering events. The Renewable Energy Policy Network for the 21st Century is a global renewable energy community of actors from science, governments, NGOs and industry. Their publication "Renewables 2022 - Global Status Report" (REN21, 2022) provides a state of the art on renewable energy. Furthermore, we kindly refer the interested reader to the "World Energy Outlook 2022" published by International Energy Agency (2022).

In the remainder of this thesis, we will focus on some specific technologies. On the one hand, we will focus on heat pumps, specifically geothermal and air-water heat pumps. On the other hand, we will examine two solar-powered technologies within the category active solar systems and, more specifically, within the subcategory solar thermal technologies. The analyses can certainly be extended to other technologies. It is important to emphasise that the focus of this thesis is not on the technologies themselves, but on the integration of the environmental impact of these technologies into the project management of construction projects.

In the next chapter, we will discuss sustainability assessment systems implemented in the construction industry. Subsequently, we will elaborate on life cycle analysis. Once the methodology has been clarified, we will carry out life cycle analyses for the four technologies mentioned above. These analyses will enable us to integrate environmental impact scores into project management processes.

3

Methodology

The pursuit of sustainable development in construction projects requires the use of techniques and tools to measure and compare of the sustainable impact of decisions made by project teams. After an introduction to sustainability assessment techniques, we elaborate on the technique we will employ in our analysis in Chapter 4, namely life cycle analysis.

3.1 Sustainability assessment systems in the construction sector

Practitioners, such as project managers, can apply assessment systems to evaluate or differentiate a particular product, building or design. Globally, there are hundreds of building evaluation tools (Fowler & Rauch, 2006) that focus on different domains of sustainable development and are designed for different types of projects. Typical examples of these tools (Heinzerling et al., 2013; Hoogmartens et al., 2014) include life cycle assessment, life cycle costing, exergy analysis, energy system design, cost-benefit analysis, indoor environmental quality assessment, operation and maintenance optimisation, and many more. We are going to focus on sustainable building rating systems, which are defined by Fowler & Rauch (2006) as "tools that examine the performance or expected performance of a 'whole building' and translate that examination into an overall assessment that allows for comparison against other buildings". These include a set of explicit performance thresholds that buildings must meet to be certified, as well as specific guidelines that can assist project teams in meeting or exceeding those performance thresholds (Shan & Hwang, 2018). In other words, these tools (Shan & Hwang, 2018) inform people how environmentally friendly and ecological a building is and identify the sustainable principles and practices that have been applied. Specific examples (Doan et al., 2017; Fowler & Rauch, 2006; Mahmoud et al., 2019; Nguyen & Altan, 2011) used in practice all over the world are LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Assessment Method), CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), GBTool, Green Globes, Green Star and HK-BEAM.

Although these tools each have the same objective, Saunders (2008) detected significant disparities between the results of the assessment tools for which essentially the same rating was expected. This is because the instruments differ in terms of assessment characteristics, assessment model and weighting scheme according to the regional variations of the country of origin (Banani et al., 2013; Mahmoud et al., 2019). On the one hand, it can be argued that this is acceptable since each country has its own individual characteristics, such as climate and type of building stock, making an individual sustainability assessment tool for that country considered advantageous (Reed et al., 2009). On the other hand, the disadvantage is the fact that the assessment tools for various countries are constructed based on different parameters (Dixon et al., 2008; Reed et al., 2009; Rezaallah et al., 2012). Consequently, this makes it difficult for stakeholders such as facility managers, designers, sustainability experts, real estate investors and project managers to compare and assess the sustainability of their technologies or buildings on a consistent basis (Mahmoud et al., 2019).

Hence, for an assessment system to add real value to the sustainable design and/or operation of a building, it must provide a credible, consistent basis for comparison, evaluate relevant technical aspects of sustainable design, and not be too burdensome to implement and communicate (Fowler & Rauch, 2006). In order to help practitioners like real estate investors compare their properties in various cities using a consistent international language, three of the well-known assessment tools, namely BREEAM, LEED, and Green Star, have already attempted to develop a global working sustainability assessment tool (Kennett, 2009). However, the idea of developing a global working assessment tool has not yet been developed as it is hampered by several gaps outlined by Mahmoud et al. (2019). These gaps include the lack of a unified set of sustainability assessment attributes and the lack of a consensus-based approach to calculating weights and assigning weights to assessment criteria. As a result, their research introduces a generic assessment model with different formulas to assess the sustainability of buildings using multi-level weighting. This tool is able to determine the current sustainability of buildings, can compare the sustainability assessment between different regions using consistent assessment attributes and assessment model, and can identify sustainability weaknesses that need more attention based on the assessment. However, the developed rating model still has a few limitations that can be examined and developed upon in future research for which we refer to the chapter entitled Discussion.

Current assessment tools are also criticised for their suitability to assess the built environment in terms of the multidisciplinary concept of sustainability. Gou & Xie (2017) reviewed critiques of green building and compared suggestive frameworks for sustainable design, which allowed us to extract an interesting and important insight. They were able to observe that the emerging importance of topics such as social and economic sustainability, life cycle assessment and climate change were not yet fully covered by these rating systems and their indicators. Most of the instruments were excessively focused on environmental sustainability, relegating the social, economic and institutional aspects of sustainability to the background with little or no attention paid to them. (Zhang et al., 2014). Addressing this criticism of current green building design and assessment tools requires an expansion of the indicator system and a more flexible framework that can be adapted to different contexts in order to cover sustainability in a more holistic way (Gou & Xie, 2017). We encountered the same conclusion in review papers that were not related to the construction industry as well. Hassan et al. (2017) acknowledged the conclusion that many studies which used sustainability assessment methods in product design mainly ignored the social but also the economic aspect. Hence, it remains a challenge regarding the evaluation of the sustainability of technologies to provide an assessment and comparison of their impacts which leverages the interconnection between all pillars of sustainability (Watanabe et al., 2016).

Classification

The various sustainability assessment systems commonly used in practice nowadays can be classified in different ways. The first classification we discuss relies on the idea that sustainable assessment systems range from energy performance evaluation to multi-dimensional quality assessment. Berardi (2012) categorised assessment tools into cumulative energy demand (CED), life cycle assessment (LCA) and total quality assessment (TQA). In this context, CED focuses on energy consumption, LCA on environmental aspects and TQA on both environmental, economic and social aspects. Second, according to Fenner & Ryce (2008), the assessment tools can be divided into the following three categories: 1) knowledge-based tools consisting of manuals and information resources, etc., 2) performance-based tools using LCA, and 3) building rating tools consisting of checklists and credit calculators. Since many tools use life cycle analysis, it seemed a valuable starting point to initiate our analysis with an LCA. The method is explained in more detail in the following section.

3.2 Life cycle analysis

Without detracting from the other pillars of sustainable development, from this point forward we will focus primarily on the environmental impact of project team decisions. What do we mean by environmental impact? It includes not only the impact of emissions on the environment, but also the impact of resource extraction and consumption. Furthermore, environmental impacts include those associated with the manufacture and assembly of materials or products, as well as those during their use and at the end of their life (collection/sorting, reuse, recycling, waste disposal) (Rebitzer et al., 2004). These emissions and wastes contribute to a wide range of impacts, including the following: climate change, stratospheric ozone depletion, eutrophication, acidification, toxicological stress on human health and ecosystems, resource depletion, water use, land use, and so on (Rebitzer et al., 2004).

To evaluate the life cycle environmental sustainability of green technologies in the construction sector, we will employ a robust and science-based method, namely life cycle analysis. We can define life cycle analysis (ISO, 2006a) as "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle", including the extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal (Ilgin & Gupta, 2010). In addition, LCA (ISO, 2006a) can help to 1) identify opportunities to improve the environmental performance of products at different stages of their life cycle, 2) inform decision makers in industry, government or non-governmental organisations, 3) select relevant indicators of environmental performance, and 4) support marketing (e.g. an eco-label scheme or an environmental claim). Hence, we can argue that this analysis technique can provide the results that allow the environmental impact of technologies to be included in the decision-making process of certain projects.

A life cycle analysis is a methodological framework which consists of four major steps as shown in Figure 3.1. These phases are interrelated with each other, requiring consistent decisions while executing the method. The double arrows between phases indicate the interactive and iterative nature of LCA (Jensen et al., 1998), as illustrated by the following examples: the impact assessment may reveal that certain information is missing, which means that the inventory analysis needs to be improved, or the interpretation of the results may be insufficient to meet the requirements of the actual application, which means that the objective and scope need to be revised.

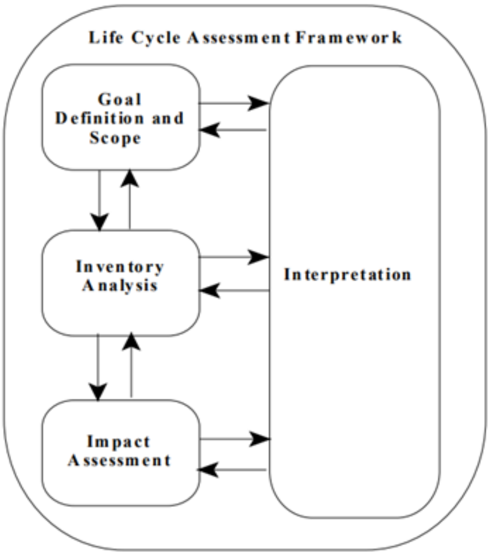


Figure 3.1: Phases of a life cycle analysis (ISO, 2006a)

The framework that is required to effectively conduct an LCA is described in detail in the ISO standards series "ISO 14040: Principles and Framework" (ISO, 2006a) and "ISO 14044: Requirements and Guidelines" (ISO, 2006b). In this chapter, we will briefly describe these four steps theoretically and apply them to the example of a geothermal heat pump. Chapter 4 presents our analysis of different green technologies used in the construction industry, including the geothermal heat pump. This analysis allows us to calculate an environmental score for each technology and even calculate their impact on each individual impact category. On this foundation, we can interpret the results and provide a thorough evaluation and comparison.

In our life cycle analysis, we will not fully conform to the ISO standards (ISO 14040 and ISO 14044). For an LCA that is fully compliant with the ISO 14040/14044 standards, the life cycle inventory stage (Bjørn et al., 2018) is a very important and time consuming step as this step include the collection of data and the modelling of the flows to, from and within the product system(s). For this purpose it is important to acquire foreground data to model the system, possibly supplemented by background data from databases and scientific literature for processes in the background system. Background data can be, for example, the data for production of generic materials, energy, transportation and waste management (Pré, 2016a). The separation between foreground and background systems is not straightforward. It depends on the focus of your research and the degree of influence of construction actors on impact causes (Silva et al., 2020). Collecting the foreground data from companies or government institutions, among others, would add little value in our thesis compared to the time and effort involved. Therefore, we will only use secondary data. In this way, we deliberately deviate from the ISO 14040/14044 standards, because in this thesis we focus on demonstrating the usefulness of LCA in the field of project management.

Step 1: Goal and Scope

Goal and scope definition provides the context for the assessment determining to whom and how results obtained should be communicated (Watanabe et al., 2016). This step includes the detailing of technical information, such as a detailed definition of the product, its life cycle and the function it performs; a definition of the functional unit; the system boundaries; the data quality requirements; the requirements regarding impact assessment procedure and subsequent interpretation and finally, but also importantly, the assumptions and limitations of the study (Watanabe et al., 2016).

Ideally, our rationale for conducting a life cycle analysis would be to assist project managers and their teams in their decision making. In doing so, we would make them aware of the dominant indicators that determine the environmental impact over the life cycle of a specific technology and enable them to identify the most contributing technologies (or even materials). This allows project teams to objectively compare the environmental performance of technologies (or materials). Some LCA software, such as One Click LCA (One Click LCA Ltd, 2023a), support ISO standards and different types of certifications making it even possible to get LCA results benchmarked against certifications like BREEAM or LEED certifications.

However, as we do not collect foreground data, we have chosen to rely on underlying processes rather than model systems. In the case of our geothermal heat pump, we will be analysing the heat production process rather than modelling an entire heat pump system. This means that the impact indicator values will only relate to these heat production processes. Our recommendations to project teams will only be based on these underlying processes, which means that we will not be able to help them identify the technologies and materials that contribute most to the environment. In order to provide comprehensive and reliable advice, all relevant data should be considered, including extraction and production of heat pump materials, transport, etc. This would require foreground data on all components and processes associated with a particular geothermal heat pump. Our decision has significant implications, making it certainly an opportunity to explore this further potential in the Discussion chapter. For the interested reader in reliable life cycle assessments of ground source heat pumps, we refer to Bonamente & Aquino (2017); Greening & Azapagic (2012); Koroneos & Nanaki (2017) and Smith et al. (2021).

The goal and scope definition of an LCA provides a description of the product system in terms of a functional unit and the system boundaries. In our highly simplified analysis, it is not possible to determine a functional unit or system boundaries since we only consider the heat delivery process. Nevertheless, for completeness and clarity, we provide some suggestions that could ideally be adopted as functional unit or system boundaries.

The functional unit can be defined as "a quantitative description of the service performance (the needs met) of the product system(s) under study" (Rebitzer et al., 2004). In the case of the ground source heat pump, the functional unit can be described as heating 416 100 L of water to 60°C, for example (Saoud et al., 2021). Evidently, these numbers were not chosen at random. For the sake of argument, it is worth making a few assumptions: the lifetime of systems is assumed to be 10 years, the average consumption of hot water per person per day is 30 litres, and we assume 3.8 people in 1 household. Subsequently, we can calculate the volume of water to be heated to 60°C for an average household for 10 years:

$$V = 30\,\frac{L}{person * day} * (10\ years * 365\,\frac{days}{year}) * 3.8\,\frac{people}{household} = 416\,100\ L\ per\ household\ for\ 10\ years \tag{3.1}$$

These calculations made it possible to formulate a functional unit by which alternative goods or services could be analysed and compared.

Additionally, choices regarding system boundaries also affect the results of an LCA study. A cradle-to-grave approach (Curran, 2017; Saoud et al., 2021) that takes into account the life cycle stages raw material extraction, manufacturing, installation, operation to disposal would be a valuable choice in this context. Practically, the system boundaries in the case of a cradle-to-grave approach for a ground source heat pump (Greening & Azapagic, 2012; Sevindik et al., 2021) include extraction and production of raw materials; all transportation; fabrication of heat collector, underfloor heating system, heat pump and assembly; installation including drilling; the generation of electricity for circulating the heat-transfer fluid through the system; maintenance of refrigerant for heat pump and disposal of materials (reuse, recycling, landfill, etc.).

The choices and assumptions made while establishing the goal and scope clearly have a major impact on the results of an LCA study. This phase helps to conduct the life cycle assessment consistently throughout the following phases (Goedkoop et al., 2016). The next stage in a life cycle analysis, after defining the objective and scope, is the inventory analysis, which we discuss in more detail in the next section.

Step 2: Life Cycle Inventory

During the time-consuming life cycle inventory (LCI) phase of an LCA (Bjørn et al., 2018), data are collected and flows into, out of and within the product system(s) are modelled. Life cycle inventory is "a method for estimating the consumption of resources and the amounts of waste streams and emissions caused by or attributable to a product's life cycle" (Rebitzer et al., 2004). Consequently, the LCI phase results in a list of quantified elemental flows that cross the system boundary of the studied life cycle and this is the input for the impact assessment phase (Bjørn et al., 2018).

Importantly, this LCI phase definitely needs to be aligned with the goal and scope setting where we have established the system boundaries. To visually represent the life cycle of a geothermal heat pump, we created a life cycle flow diagram shown in Figure 3.2. This diagram helps represent system boundaries (Curran, 2017), specifically where the analysis of the specific life cycle begins and where it ends, and what activities are part of the product system. After a conversation with Kenneth Dobbelaere, co-manager of Dobbelaere installation techniques NV, and other companies, such as Ecoheating, Selftech and Viessman, we came to some interesting insights that helped us create a life cycle flow diagram. In making this diagram, we were also inspired by the research conducted by Greening & Azapagic (2012). The colours make the various life cycle stages easily visible.

Data collection for reliable life cycle analyses that complies with ISO 14040/14044 standards uses foreground data from companies, measurements or theoretical calculations for the data needed to model your system. Background data from LCI databases or scientific literature can be used for data from production of generic materials, energy, transportation and waste management, among others (Goedkoop et al., 2016). Certain studies are quite transparent and provide (part of) their life cycle inventory data (Greening & Azapagic, 2012; Koroneos & Nanaki, 2017; Simon et al., 2021; Smith et al., 2021).

We performed the LCA in the software SimaPro (version 8.5.2.0) (SimaPro, 2023) because it incorporates several impact

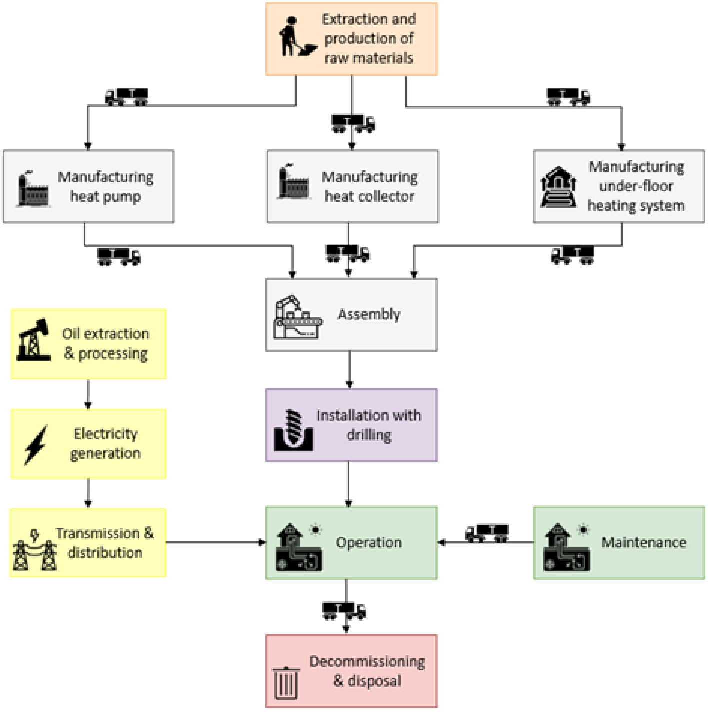


Figure 3.2: Life cycle flow diagram of geothermal heat pump (Adapted from Greening & Azapagic (2012))

assessment methods and an extensive inventory of databases. The data used in our analysis in Chapter 4 were collected from the Ecoinvent (version 3.4) database (Ecoinvent, 2022). Our heat production process has some inputs from nature such as: $1.32 * 10^{-3}$ kg carbon dioxide (air); $1.33 * 10^{-6}$ kg potassium chloride (ground); $6.41 * 10^{-7}$ m^3 water, salt, sole (water); 0.40 kg nitrite (river); 0.33 kg carbonate (ocean); 0.80 kg chromium (groundwater) and many more.

We would like to emphasise that data quality is one of the key concerns of LCA. Data quality is defined in ISO 14040 (ISO, 2006a) as “characteristics of data that relate to their ability to satisfy stated requirements”. This means that the quality of a given LCI model, datasets or database according to ISO depends entirely on the stated requirements. Changing requirements will therefore change the quality of the given data (Ciroth, 2021).

Step 3: Impact Assessment

The third phase involves life cycle impact assessment (LCIA), which is "a methodological framework for estimating and assessing the environmental impacts and resources used attributable to the life cycle of a product", such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise and others (Finnveden et al., 2009; Rebitzer et al., 2004). The purpose of the life cycle impact assessment (ISO, 2006a) is to provide additional information to help assess the results of the inventory analysis in order to better understand its environmental significance.

According to the ISO standards on LCA (ISO, 2006a, 2006b), LCIA involves the mandatory steps of selection of impact categories, classification, and characterisation and the optional normalisation and weighting. This means that on the one hand, the identification of environmental impact categories relevant to the study is mandatory. On the other hand, the selection of characterisation methods and characterisation is mandatory which ensures that it is possible to sum up the contributions of all emissions and resource extraction within each impact category, and translate the inventory data into a profile of environmental impact scores (Finnveden et al., 2009). Optional normalisation expresses the relative magnitude of the impact scores on a scale common to all impact categories to facilitate the interpretation of the results (Rosenbaum et al., 2018). The weighting of the different environmental impact categories and resource consumption is also optional and reflects the relative importance given to them in the study and thus in accordance with the goal and scope definition (Finnveden et al., 2009). By assigning weights to each impact category, it is possible to determine which impacts are most important and how significant they are (Rosenbaum et al., 2018).

Many LCIA methods are available nowadays, making the choice really difficult and resulting in few newly developed methods by LCA practitioners (Rashid & Yusoff, 2015; Rosenbaum et al., 2018). Although these methods follow the same steps (usually, characterisation, normalisation and weighting), each method addresses different impact categories, considering specific nomenclatures and using different taxonomies to classify their outputs (Carvalho et al., 2014).

However, we can divide life cycle impact assessment methodologies into midpoint and endpoint approaches. Midpoint approaches convert emissions of hazardous substances and extractions of natural resources into impact category indicators at the midpoint level (such as acidification, climate change, and ecotoxicity), whereas endpoint approaches are LCIA methods with impact category indicators at the endpoint level, i.e. the level of protection areas (such as damage to human health and damage to ecosystem quality) (Heijungs et al., 2003; Van Hoof et al., 2013). Finnveden & Potting (2014) clarify this with an example concerning climate change. Greenhouse gases such as CO_2 and CH_4 cause an enhancement of the atmosphere's ability to absorb infrared radiation. This is one of the first impacts after emission and is usually used as a midpoint indicator of climate change (i.e., by expressing greenhouse gases in kilograms of CO2 equivalents). This effect of the absorbed infrared radiation in turn leads to a chain of other effects, for example, an increase in the heat content and temperature of the atmosphere, which in turn cause changes in regional and global climate and sea level rise, and ultimately lead to damage in each of the protection areas: human health, natural environment and natural resources. These three are referred to as endpoint indicators.

In our analysis, we will use the IMPACT 2002+ methodology (Humbert et al., 2014; Jolliet et al., 2003), which represents a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results to 4 damage categories via 15 midpoint categories. The 4 damage categories named 'human health', 'ecosystem quality', 'climate change' and 'resources' are linked to the LCI results through 15 midpoint indicators ('carcinogens', 'non-carcinogens', 'respiratory effects', 'ionising radiation', 'ozone layer depletion', 'photochemical oxidation', 'aquatic ecotoxicity', 'terrestrial ecotoxicity', 'terrestrial acidification/nutrification', 'aquatic acidification', 'aquatic eutrophication', 'land occupation', 'global warming', 'non-renewable energy', 'mineral extraction'). A limitation of this method (Jolliet et al., 2003) is that several categories of effects have not yet been considered, such as effects on the marine environment, noise, etc. Nevertheless, many researchers in the construction industry use this methodology for both midpoints and endpoints assessments (Ortiz et al., 2009; Rashid & Yusoff, 2015).

By explaining environmental impact it becomes clear that LCA is not a straightforward task. Many subjective choices and decisions have to be made to determine the environmental impact of products, technologies or buildings. For example, the choice of environmental impact assessment method introduces uncertainty into LCA (Cellura et al., 2011) as each method assesses impacts using different characterisation factors, but there is no unique correct choice. This example illustrates why it is not a matter of course to calculate environmental impacts and compare different products using LCA. Consequently, it is extremely important to consider both complexity and uncertainty when applying LCA (McManus & Taylor, 2015).

Step 4: Interpretation

To conclude the discussion of the four-stage framework of life cycle assessment, we will discuss the last phase namely interpretation. The purpose of interpretation (ISO, 2006a; Khasreen et al., 2009) is to analyse results, perform uncertainty and sensitivity analysis, draw conclusions, explain limitations and make recommendations based on the findings of the previous phases of the LCA or LCI study and report the results in a transparent, understandable, consistent and complete manner.

The interpretation (Hauschild et al., 2018) proceeds in three interrelated steps. First, the significant issues (key processes and assumptions, most important elementary flows) are identified throughout the different phases of the LCA. Afterwards, these issues are evaluated for their impact on the overall results of the LCA and the completeness and consistency with which they were addressed in the study. Finally, the results of the evaluation are used in formulating conclusions and recommendations from the study.

We can certainly conclude that all decisions made during the LCA (choice of functional unit, boundaries of the LCA system, inventory data, choice of impact assessment method, etc.) have a major impact on the LCA results, and thus on the environmental value of a technology, material, building or other object under study (Cabeza et al., 2014). Reviewing different life cycle analyses of for example geothermal heat pumps, we can confirm that the conclusions of the different studies significantly differ depending on the goal and scope definition and other important decisions such as data being country specific. Hence, during our analysis we will examine the alternative technologies from a project management technical perspective. Consequently, in Chapter 5, we elaborate on how this environmental impact can evolve during a given activity of a project.

Having clarified the methodology, it is also interesting to reflect on the limitations of life cycle analysis in the construction sector. We will discuss this in more detail in the next section.

Critiques of LCA in the construction sector

On the one hand, the importance of LCA as a scientific tool to assess environmental impacts in the construction sector (Buyle et al., 2013) is growing rapidly, but on the other hand, there are still many research opportunities and areas where current practice can be improved. Below we briefly describe four shortcomings or research opportunities of LCA in the construction sector.

The critical review of Dossche et al. (2017) shows that the LCA research is still in a fragmented state, as a result of the presence of numerous unspecific guidelines and different interpretations of those guidelines. The international standards on LCA, namely ISO 14040/44, only provide a general framework, and not an exact technique to calculate environmental impacts, which is why it is possible to make an LCA with different boundary conditions (Cabeza et al., 2014; Dossche et al., 2017; Khasreen et al., 2009). A valuable comparison between different LCAs is therefore difficult.

Second, a review of several cases focusing on an analysis of whole buildings (Buyle et al., 2013; Cabeza et al., 2014) indicates that the dominance of the use phase is a recurring conclusion, especially in conventional buildings and mainly caused by heating and/or cooling needs. In both research and policy, there was a major focus on energy reduction (Buyle et al., 2013). Partly due to regulations, new buildings are today more energy efficient, making other phases of the life cycle more important such as choice of materials, water use, construction and end-of-life (Allacker, 2010; Buyle et al., 2013). These research topics certainly deserve more attention.

The third drawback of current LCA practice in the construction sector is one we also covered in the previous section on sustainability assessment systems. Due to the environmental focus of LCA, social and economic aspects are not considered. In general, ISO restricts life cycle impact assessment to environmental impacts and does not address the other two dimensions of sustainability (Hunkeler & Rebitzer, 2005). However, attempts (Jørgensen et al., 2008) are on-going to develop LCIA for social impacts, e.g., under the UNEP/SETAC Life Cycle Initiative. Other aspects overlooked by the focus on environmental impact include quality, energetic, structural nor aesthetic requirements (Buyle et al., 2013). The research of Allacker (2010) highlighted the importance of architectural design, which is often even more effective than purely technological improvements. Certain factors that can also have a significant impact, although often ignored, are solar gains, orientation and compactness (Allacker, 2010).

A fourth drawback is evidently an important one since it concerns data quality. The review conducted by Khasreen et al. (2009) highlights not only the lack of an internationally agreed assessment methodology, but also the lack of an internationally comparable data inventory that hinders the application of LCA in the construction industry. Moreover, the review by Buyle et al. (2013) found that mostly deterministic data are used, which disadvantages the accuracy, objectivity and comparability of the study.

Despite the limitations and criticisms of LCA (in the construction sector), we still consider it a powerful tool for evaluating the environmental impacts of (green) technologies and buildings. According to the academic literature, LCA can undoubtedly make a significant contribution to sustainable development. This is due to its holistic approach, taking into account the entire life cycle of the product or building under consideration. Moreover, LCA identifies critical points in the life cycle of a product or building that contribute significantly to its environmental impact. In addition, LCA can provide environmental assessments and comparisons that are understood and relevant to a wide range of stakeholders.

In the following chapter, we will carry out life cycle analyses of different technologies used in the construction industry. Subsequently, in chapter 5, we will integrate these environmental impact scores into construction projects using a clear six-step framework.

4

Descriptive Model and Results

In chapter 2, we have already qualitatively identified the environmental advantages and disadvantages of certain technologies. To continue our research, we will provide quantitative evidence based on a life cycle analysis. In what follows, we calculate an environmental impact score for different scenarios in a project consisting of various (green) technologies. Based on these scenarios with corresponding environmental impact scores, we are able to make a well-founded choice for which scenario to choose. Involving the full life cycle of these technologies creates a high level of complexity to calculate that environmental impact score. Hence our choice to pursue a simplified analysis in this descriptive chapter as we have already described in chapter 3. We would like to reiterate here that we only consider the underlying heat production processes and thus do not include all materials and other required LCI data for a reliable and complete LCA analysis. Moreover, we restrict our analysis to two clusters of technologies. The analysis can certainly be applied to other clusters as well, but this is out of scope of this thesis. On the one hand, we focus on heat pumps, more specifically geothermal heat pumps and air-water heat pumps, and on the other hand on solar-based systems.

Many LCA studies of these two clusters of technologies can already be found in the literature. However, in our opinion, the application of sustainability assessment of these and other technologies is missing in project management. More specifically, we want to demonstrate that in addition to time and cost, it is possible to take environmental impact into account for decisions a project manager/team has to make. To illustrate this, we start from a life cycle analysis of the production of heat enabled by technologies which belong to the two clusters we focus on. Specifically, we examine the environmental impact of heat production from a ground source heat pump and from an air-water heat pump. Furthermore, we also study alternative technologies where heat is delivered with a solar system including the necessary auxiliary heating, maintenance and electricity use for operation. Under this cluster we distinguish the operation of a solar collector system in combination with electric heating (solar+electric) and gas heating (solar+gas). The life cycle impact assessment results we will present and analyse below were obtained by using SimaPro 8.5 software (SimaPro, 2023) and the ecoinvent v3.4 database (Ecoinvent, 2022).

This chapter is structured as follows. First, we will start within the cluster of heat pumps. We will examine each heat pump separately and then compare both heat pumps. Second, we will consider the cluster of solar powered systems where we also consider each technology separately and then compare both. After the comparisons within each cluster, it is also valuable to compare the technologies between different clusters. We will perform these between-cluster comparisons in the third section. This will allow a better insight into the differences at the single score level, endpoint damage categories or even midpoint damage categories. Based on these results, we can also take a look at the environmental impact of combining two technologies from different clusters. These combinations are useful and interesting, allowing us to understand peaks of indicators that amplify or peaks of indicators that flatten out. Furthermore, we also gain insight into the range of environmental impact scores that the combinations generate. In the fourth section, we will briefly discuss the application of LCA in the practice of construction project management. This is followed by a conclusion of the main insights of this chapter.

4.1 Single technology: heat pumps

4.1.1 Ground source heat pump

For this scenario, we investigate the production of heat with a ground source heat pump and a borehole heat exchanger for an average single-family house in the Swiss midland. Switzerland is assumed to represent an average climatological and geological location in Europe. The dataset that we utilised is based on the following assumptions. The ground source heat pump has a heat capacity of 10 kW and a Seasonal Performance Factor (SPF) of 3.9 (for the year 1998). The SPF (Chwieduk, 2016; Dones et al., 2004) is an indicator used for heat pumps to evaluate their efficiency, expressed as a ratio between the total heat supplied to a building (by the heating system) and the electricity consumed by that heat pump (to drive a heat pump's compressor and other heating system devices). Data for the estimation of SPF is based on a field study for Swiss heat pumps and on various literature. In addition, we assume a life time of 20 years for the heat pump and the floor heating system and 50 years for the borehole heat exchanger. Furthermore, this dataset includes emissions of refrigerant R134a during operation, but doesn't include the heat distribution in the single-family house, nor a buffer heat storage. The Ecoinvent process under investigation is called: "Heat, borehole heat pump CH| heat production, borehole heat exchanger, brine-water heat pump 10kW | APOS, S" (Ecoinvent, 2022).

For our analysis, we will use the impact assessment method IMPACT 2002+ (V2.14). This method contains 15 impact categories that allow an aggregation to a single score. After normalisation and weighting, we arrive at an environmental impact score of 5.97 µPt for this geothermal heat pump. Both the overall environmental impact score of this heat pump and the subdivision by damage category is shown in Figure 4.1. A damage category is also called an endpoint category, a damage impact score, or a damage indicator. It is defined as "the quantified representation of environmental quality change and calculated by multiplying the damage factor with the inventory data" (Humbert et al., 2014). Taking a closer look at which damage categories make up the largest share of this single score, it is by far 'resources' (58.2%) followed by 'climate change' (18.8%) and 'human health' (17%). 'Ecosystem quality', on the other hand, contributes only 5.98% to the single score value.

To make a solid comparison with other geothermal heat pumps or even other green technologies, we will take a step back in our analysis. In doing so, we examine which midpoint impact categories have the largest contribution. We consider four clusters, each of which includes one damage category and its associated midpoint impact categories. These clusters are shown in table 4.1. In this way, each midpoint category is assigned to one damage category.

In Figure 4.1, we already observed that the damage indicator 'resources' is the largest contributor to the environment for this

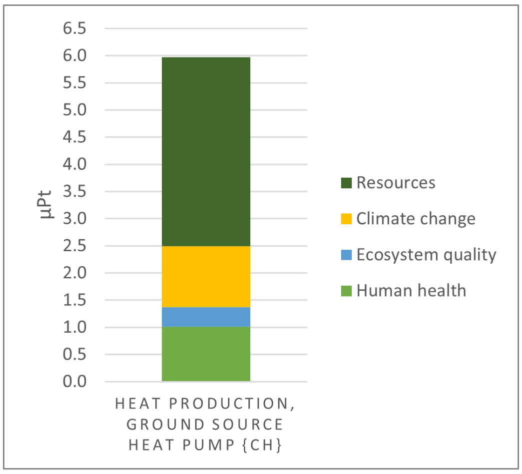


Figure 4.1: Environmental impact score ground source heat pump

Human health	Ecosystem quality	Climate Change	Resources
Carcinogens (Human toxicity)	Aquatic ecotoxicity	Global warming	Non-renewable energy
Non-carcinogens (Human toxicity)	Aquatic acidification		Mineral extraction
Respiratory inorganics	Aquation eutrophication		
Ionising radiation	Terrestrial ecotoxicity		
Ozone layer depletion	Terrestrial acidification/nutrification		
Respiratory organics	Land occupation		

Table 4.1: Clustering midpoint impact categories

ground source heat pump. Based on the clusters of midpoint indicators, we notice that the damage category 'resources' is represented by the midpoint impact categories 'non-renewable energy' and 'mineral extraction'. Figure 4.2 visually depicts the midpoint impact categories, which allows us to verify if mainly 'non-renewable energy' or 'mineral extraction' is the cause of the relatively high environmental contribution of the damage category 'resources'. The cause is clearly the production and consumption of 'non-renewable energy', which represents 99.68% of the resources and even 58.03% of the total impact score of the ground source heat pump. Overall, the geothermal heat pump we consider in this case scores especially poorly on 'respiratory inorganics', 'global warming' and 'non-renewable energy'. The other midpoint impact categories represent less than 6% of the total environmental score of 5.97 µPt.

For a project manager, these values for this particular heat pump have little value on their own. Rather, the value resides in comparing individual technologies as well as combinations of technologies and integrating their conclusions based on environmental impact into their decisions throughout the project. Therefore, we will compare the environmental impact of different technologies, both within and between clusters of technologies. Still within the heat pump cluster, we will first analyse an air-water heat pump and then compare it with the ground source heat pump. To strengthen this analysis, we will examine some scenarios for both ground source and air-water heat pumps. After the heat pumps cluster, we will move on to solar-based technologies.

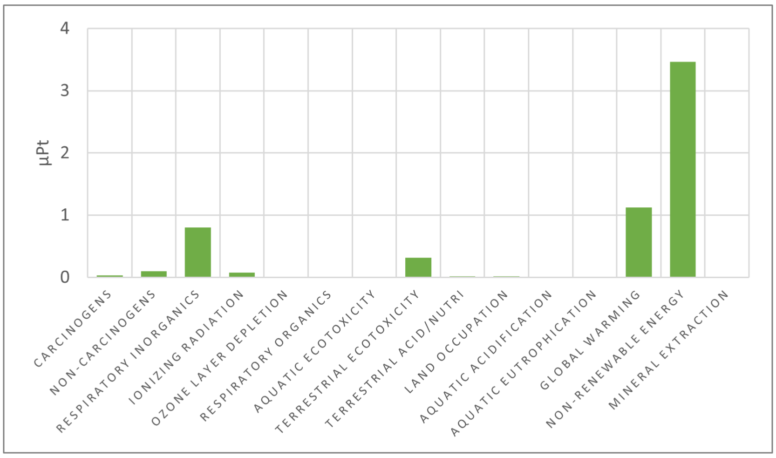


Figure 4.2: Midpoint impact scores ground source heat pump

4.1.2 Air-water heat pump

In addition to the already discussed geothermal heat pump, we also analyse the air-water heat pump within the cluster of heat pumps. In contrast to geothermal heat pumps that use the Earth's heat as a heat source, air-to-water heat pumps use ambient air as a heat source. Here water represents the heating-circuit water. Given similar assumptions regarding the scope of the heat production processes, it is permissible to compare the two. The Ecoinvent process we will scrutinise is called: "Heat, air-water heat pump 10kW CH| production | APOS, S" (Ecoinvent, 2022).

We examine the production of heat with an air-water heat pump for an average single-family house in the Swiss midland. The air-water heat pump under consideration has a heat capacity of 10 kW and a Seasonal Performance Factor (SPF) of 2.8 (for the year 1998). Like the ground source heat pump, we also assume 20 years of life time for the air-water heat pump and assume the system is operated without an auxiliary heating system. The majority of heat pumps in Switzerland operate in a monovalent way, meaning that even at low outdoor temperatures, the heat pump provides sufficient heat and an auxiliary system is not needed if buildings are well insulated and a low-temperature heating system is used (Zogg, 2002; Erb & Hubacher, 2001; Holozan, 2002). Unlike geothermal heat pumps, air-water heat pumps are often retrofitted as a heating system.

An observation of Figures 4.3 and 4.4 shows that the environmental impact score of an air-water heat pump is 7.97 µPt. This is mainly attributed to the midpoint impact categories (with decreasing magnitude): 'non-renewable energy' (3.46 µPt), 'global warming' (1.12 µPt) and 'respiratory inorganics' (0.80 µPt). Obtaining these stand-alone values for an air-water heat pump for different midpoint or damage indicators is a strong starting point for comparing technologies within the cluster of heat pumps. Later, we will also include technologies from another cluster in our analysis.

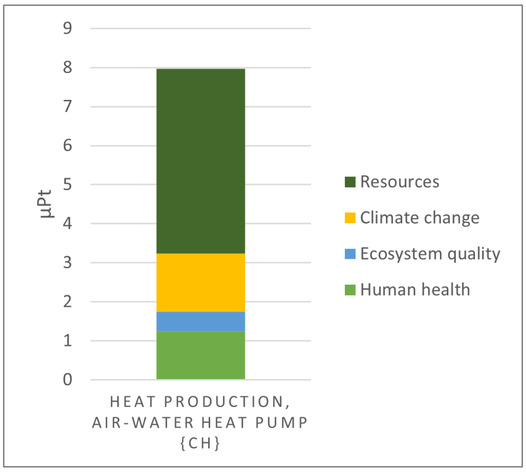


Figure 4.3: Environmental impact score air-water heat pump

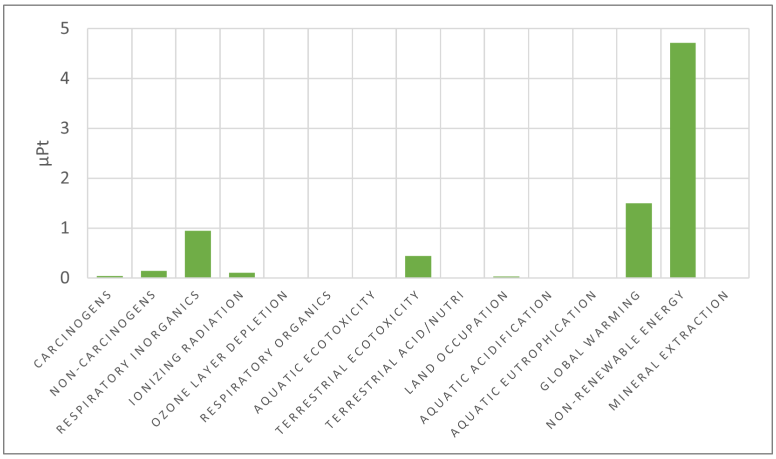


Figure 4.4: Midpoint impact scores air-water heat pump

4.1.3 Comparison ground source and air-water heat pump

In this section, we compare the production of heat in the case of using a ground source heat pump and the associated borehole heat exchanger with the case of using an air-water heat pump. However, the results are unambiguous. Based on each impact category and on the single score, we can conclude that heating using a ground source heat pump results in lower environmental impacts compared to heating with an air-water heat pump. The overall environmental impact scores of both technologies are shown in Figure 4.5.

It is not only on total environmental impact that the air-water heat pump scores worst, but also on each damage and even midpoint impact category. We found these predominant results quite remarkable and it made us reflect on our assumptions. In this thesis, we only consider the underlying heat production processes, which does not necessarily mean that we can extend our conclusions from these processes to complete heat pump systems. Consequently, it seemed interesting to verify our results against existing scientific literature of LCA on these two heat pumps.

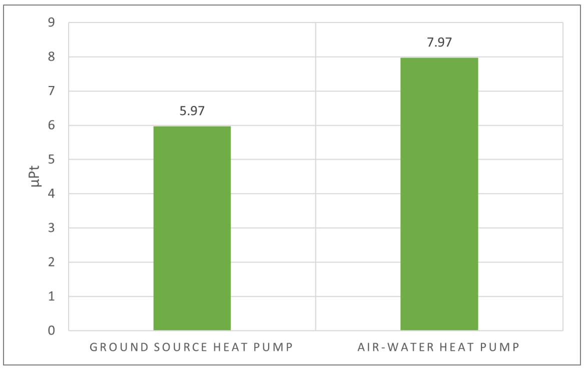


Figure 4.5: Environmental impact scores ground source heat pump and air-water heat pump

Greening & Azapagic (2012) applied a different impact assessment method, but came up with similar results. According to them, the worse environmental score of the air-water heat pump is due to lower efficiency and higher usage of electricity. The large contribution of electrical energy required to drive heat pumps was confirmed by the critical review by Marinelli et al. (2019). Moreover, they concluded that the production and use phases have the largest environmental impacts with an average contribution of about 36% and 50%, respectively. However, it is worth adding the critical note that the results of the various LCA studies can differ considerably due to different assumptions regarding Seasonal Performance Factor, life cycle inventory data (e.g. choice of materials), scope of the study and so on.

These results regarding the environmental differences of the two heat pumps are very meaningful to include in project management decisions anyway, in addition to the parameters of time and cost. Still, we thought it would be interesting to already reflect on the future as well. Based on the current problems in the world, we were able to draw up some scenarios that might happen in the future. On the one hand, 'land occupation' is an increasingly pertinent issue, while 'non-renewable energy' and 'global warming' are also relevant concerns to explore.

Especially in cities, but also in other places in the world, **'land occupation'** is becoming increasingly important due to the ever-growing population. However, we could not measure the effect of increasing importance of 'land occupation' as the values for the impact indicators were so low for both heat pumps. This is also logical since these technologies do not occupy much space. In addition to land occupation, many other midpoint impact indicators have very low values for both heat pumps. Consequently, increasing these values will have little impact on the overall impact score and conclusion. Hence, we exclude these scenarios as they offer limited added value.

Both heat pumps do have high values for **'non-renewable energy'**, because of the electrical energy required to drive heat pumps. Evidently, the use of 'non-renewable energy' is also heavily pressured, and the pressure will only increase in the future. Hence, we will first analyse the increasing effect of the midpoint impact indicator 'non-renewable energy'. Second, we will also examine the effect that **'global warming'** would have on increasing attention of project managers and property managers, among others. We will explore with curiosity whether it will influence our decision for a particular technology.

Scenario analysis

In this first scenario we investigate the impact of an increasing relevance of **'non-renewable energy'**. Since this category provides the greatest direct impact on the single score, an increase in importance of this category has the strongest effect relative to other impact or damage categories. The other indicators remain as relevant as before. Specifically, we adjusted the weights of the impact indicators to obtain a 20% increase in the environmental impact scores for the 'non-renewable energy' category while keeping the values of the other categories constant.

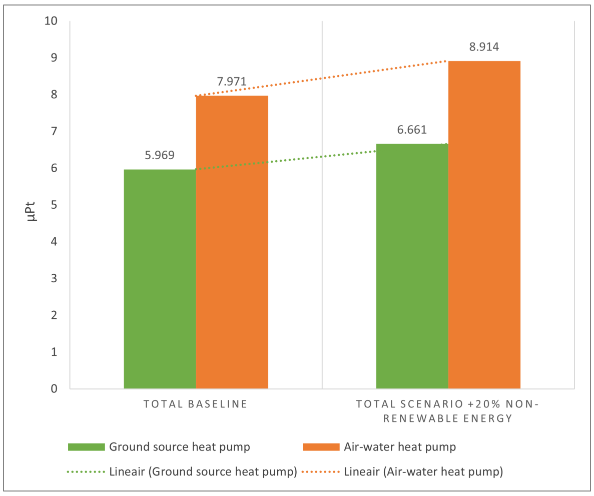
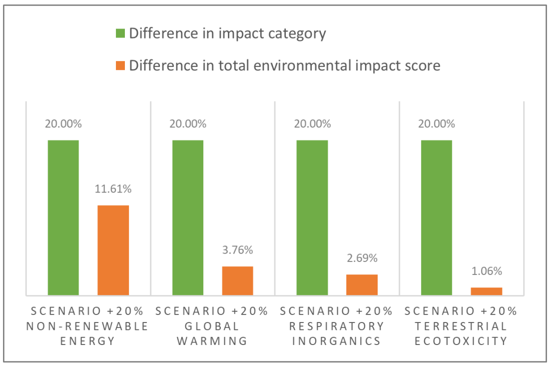


Figure 4.6: Environmental impact scores of heat pumps in scenario 20% increase in 'non-renewable energy' category

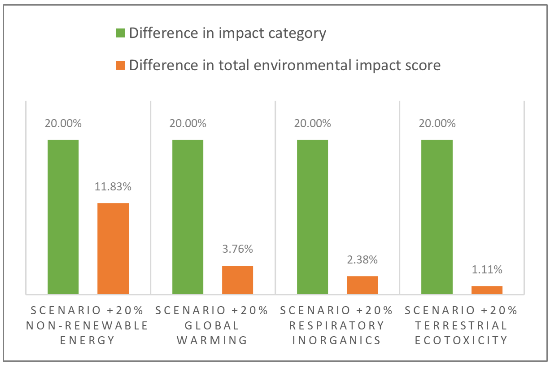
As illustrated in Figure 4.6, we clearly notice an increase in the total impact score of both heat pumps due to increasing importance of this one category. In the case of ground source heat pumps the overall environmental impact score increases by 11.60% and in the case of air-water heat pumps the increase amounts to 11.83%. The slightly larger increase in this second case is due to the initially higher value of the category whose weight we increased, namely 'non-renewable energy'. A second reason is the initial slightly larger weight of the category relative to the overall impact score. The 'non-renewable energy' category weighs 1% more in the case of the air-water heat pump than in the case of the ground source heat pump.

We repeat the same procedure but now in the case of increasing relevance of **'global warming'** while the other indicators remain constant. Our suspicions of a smaller expected impact is confirmed because for both heat pumps we notice a 3.76% increase in the total environmental impact score. This increase is noticeably smaller due to the initially lower values of the baseline scenario and because 'global warming' contributed less to the total impact score anyway compared to 'non-renewable energy'.

Based on these findings, it can be confirmed that increasing the impact categories that contribute almost nothing to the total impact score will have little to no effect. There are four midpoint impact categories that have a significantly positive contribution to the environment in the case of heat pumps, namely 'non-renewable energy', 'global warming', 'respiratory organics' and 'terrestrial ecotoxicity'. Hence, an increase in any of these values would be more noticeable. For completeness, we provide a brief visual overview of the effects of the four most contributing midpoint categories to the overall environmental impact score in Figure 4.7.



(a) Percentage differences for ground source heat pump



(b) Percentage differences for air-water heat pump

Figure 4.7: Percentage difference in total environmental impact score due to 20% increase in one midpoint impact category

Based on Figure 4.7, we can conclude that especially an increase in 'non-renewable energy' has a significant effect on the overall environmental impact score of the technology and consequently on the decisions of practitioners in the industry. Increasing relevance in the future of other midpoint impact categories yields less pronounced changes in the overall impact score.

The results of our analysis within the cluster of heat pumps are already very interesting, but we want to go a step further. A heat pump is only one option for heating a building. If we have a heating activity in a construction project, we can link different technologies to it. In addition to heat pumps, we will also discuss solar-based technologies that pursue the same goal of heat production. This will allow us to compare the technologies of the two clusters at a later stage.

4.2 Single technology: solar systems

In Chapter 2, we have already discussed the wide variety of technologies using solar energy. The technologies that we will now examine in more detail can be classified as active solar systems, and more specifically as solar thermal technologies, which are discussed in Section 2.1.2. Specifically, we investigate the production of heat by a solar space and water heating system. These LCI data are also available in the Ecoinvent database. This includes the allocation to each megajoule (MJ) of heat delivered of the effects of the production of the system, its maintenance and the electricity used to operate the recirculation pumps (Ecoinvent, 2022). In addition, the required auxiliary heating is taken into account, and for this we distinguish different scenarios. The auxiliary heater can use electricity, natural gas or wood as its energy source.

The solar space and water heating system proves to be an effective technology to convert solar energy into thermal energy (Jaisankar et al., 2011). In addition to this auxiliary heating (electricity, natural gas or wood), a solar water heating system also includes solar collectors mounted on the roof and a separate hot water tank (Hang et al., 2012; Raisul Islam et al., 2013). The considered system uses fluids, either water or an antifreeze solution, as a medium for energy transfer and storage (Klein et al., 1976). The solar collectors are used to heat the liquid, which is then circulated through the storage tank and heats the water. The heated water from the storage tank flows through one or more heat exchangers after which it can be used by your heating system, such as in an underfloor heating system. An auxiliary heating system is used to raise the water temperature during periods when less heat is available from the solar collector (Jamar et al., 2016; Biglarian et al., 2021). Within this cluster of solar space and water heating systems, we distinguish between three scenarios depending on the auxiliary heating system, namely solar+electric, solar+gas and solar+wood.

The Ecoinvent heat production processes we will investigate are called (Ecoinvent, 2022):

- "Heat, **solar+electric**, multiple-dwelling, for hot water CH| heat production, at hot water tank, solar+electric, flat plate, multiple dwelling | APOS, S"
- "Heat, **solar+gas**, multiple-dwelling, for hot water CH| heat production, at hot water tank, solar+gas, flat plate, multiple dwelling | APOS, S"
- "Heat, **solar+gas**, one-family house, for combined system CH| heat production, at solar+gas heating, flat plate, one-family house, combined system | APOS, S"
- "Heat, **solar+gas**, one-family house, for combined system CH| heat production, at solar+gas heating, tube collector, one-family house, combined system | APOS, S"
- "Heat, **solar+gas**, one-family house, for hot water CH| heat production, at hot water tank, solar+gas, flat plate, one-family house | APOS, S"
- "Heat, **solar+wood**, one-family house, for combined system CH| heat production, at solar+wood heating, flat plate, one-family house, combined system | APOS, S"

These processes have a similar scope as they all account for the production of heat with a solar system including the necessary auxiliary heating, maintenance and electricity use for operation. An exploration of the environmental impact scores and the underlying damage and midpoint impact categories of the six processes listed above clarified that the four solar+gas processes consistently had similar values. Hence our decision to average these four solar+gas processes. This visually facilitates the comparison between the three scenarios solar+electric, solar+gas and solar+wood.

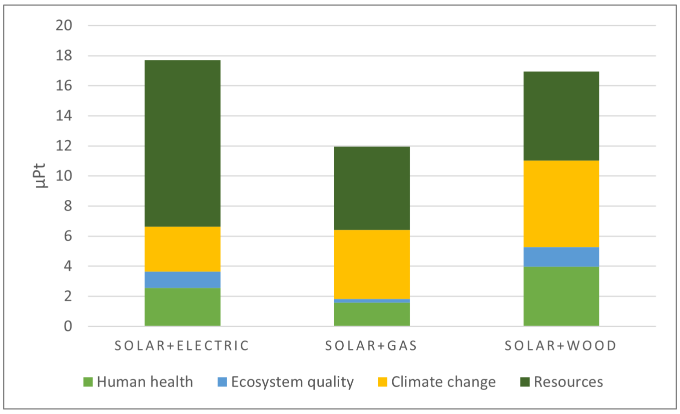


Figure 4.8: Environmental impact scores of different solar systems

Figure 4.8 plots the total environmental scores for the three scenarios with the subdivision of the different damage categories. Calculating environmental scores for these technologies results in interesting conclusions. First of all, we notice a significant difference between the combination solar+gas compared to the combinations solar+electric and solar+wood. In general, solar+gas is clearly more beneficial. If we consider each damage category individually, we notice that this is mainly due to more favourable values for 'human health' and 'ecosystem quality'. In addition, the large value for solar+electric for 'resources' is remarkable. This value is about slightly less than twice as large as for the other combinations. This large difference is entirely due to the midpoint impact category 'non-renewable energy'. In contrast, for the damage category 'climate change', solar+electric has the most favourable value. Furthermore, it is also notable that solar systems have similar peaks for damage and midpoint impact indicators compared to heat pumps. For solar systems, we also see higher values for (in decreasing magnitude) 'non-renewable energy', 'global warming', 'respiratory inorganics' and 'terrestrial ecotoxicity'.

Substantiating these results with the scientific literature is not evident. The important role solar thermal systems can play in reducing energy consumption in the building sector is already widely recognised, yet few LCA studies can be found regarding building integrated solar thermal systems (Lamnatou et al., 2015). The relevant studies that exist to validate our results obviously rely on specific assumptions. We have decided that these studies do not provide sufficient foundation to draw general conclusions to compare our results with.

After this introduction and analysis of solar space and water heating technologies, we will again include heat pumps in our analysis in the next section. First, we will compare the four technologies individually and then we will examine the impact when multiple technologies are implemented in the same project.

4.3 Combining two technologies

So far, we can reflect on some useful and clear insights. We are already able to identify the most environmentally friendly technology for heat production within each cluster. However, it is important to reiterate that we are only considering the underlying heat production processes and do not take into account the different materials and fluids used etc. To continue our analysis, we will first assess the environmental impacts of technologies from different clusters, and then combine technologies and examine their impacts. Wood is used significantly less as auxiliary heating, which is why we decided to abandon solar+wood technology and focus on geothermal heat pump, air-water heat pump, solar+electric, solar+gas.

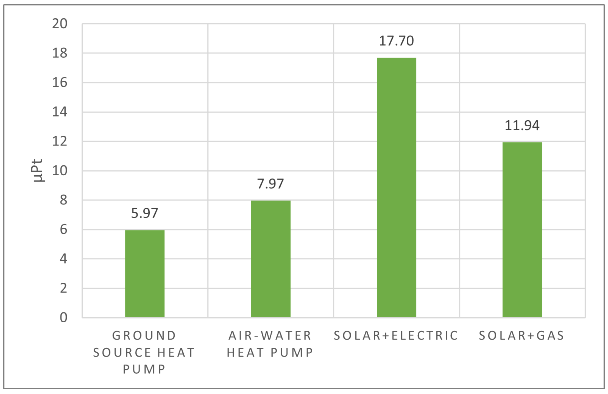


Figure 4.9: Environmental impact scores of four different technologies

Based on the environmental scores shown in Figure 4.9, we notice that the heat production processes of solar systems

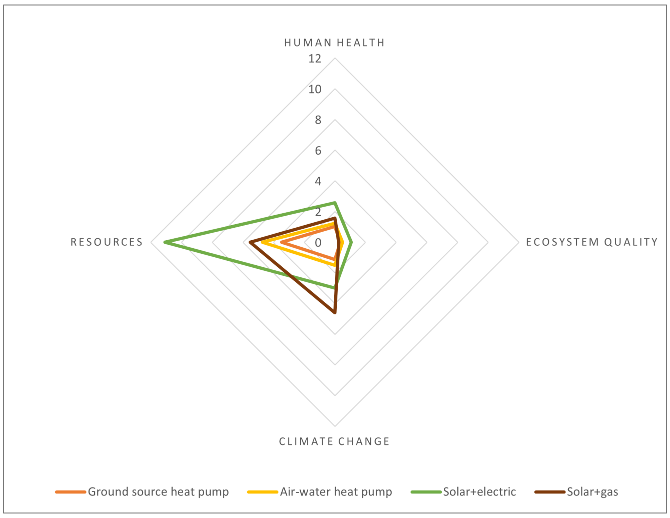


Figure 4.10: Environmental impact scores per damage category for four different technologies

generally have a worse environmental impact than those of heat pumps. In particular, solar+electric outperforms the other technologies in a negative sense. What is interesting now is to examine the differences at the various midpoint and endpoint impact categories. Figure 4.10 visually shows the damage impact indicators for the four scenarios under consideration. These figures clearly illustrate the large negative environmental impact of solar+electric in terms of 'resources' (damage indicator) and specifically of 'non-renewable energy' (associated midpoint indicator). Solar+gas systems also performed worse in terms of environmental impact compared to heat pumps. This is largely due to damage categories 'climate change' and a little due to 'resources'. The differences between the two types of heat pumps appear to be relatively small for most indicators. In general, major differences are especially noticeable for the intermediate impact indicators 'non-renewable energy' and 'global warming'. For the other indicators, the differences are relatively smaller.

From a purely environmental point of view, we would undoubtedly opt for a heat pump based on the information we know at this stage. The difference in environmental impact scores between the two investigated heat pumps is relatively small compared to solar technologies. Having completed the analysis for individual technologies, we can now examine combinations of technologies in terms of environmental impact.

4.3.1 Combinations based on sum

In some cases, a single technology may be sufficient to meet the heating needs of a particular building. Moreover, one technology does not exclude the other. This means that we can combine technologies from two different clusters to produce more heat. However, using two technologies results in a larger environmental impact than a single technology. For example, both the heat pump and the solar system need to be manufactured, assembled, used and disposed of. In our subsequent analyses, we use the sum to combine technologies from different clusters, ignoring possible interaction effects.

Figure 4.11 indicates that the high environmental score of the solar collector system with electric heating is so prevalent that

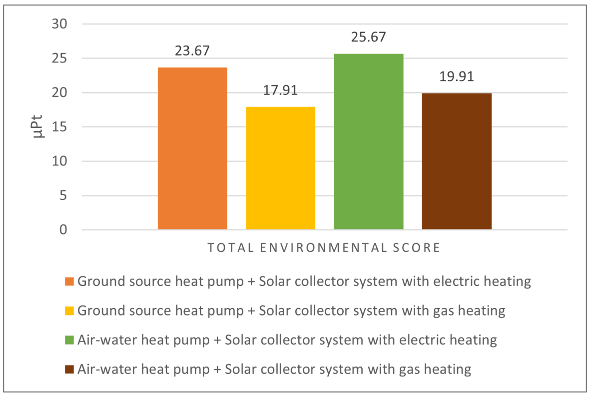
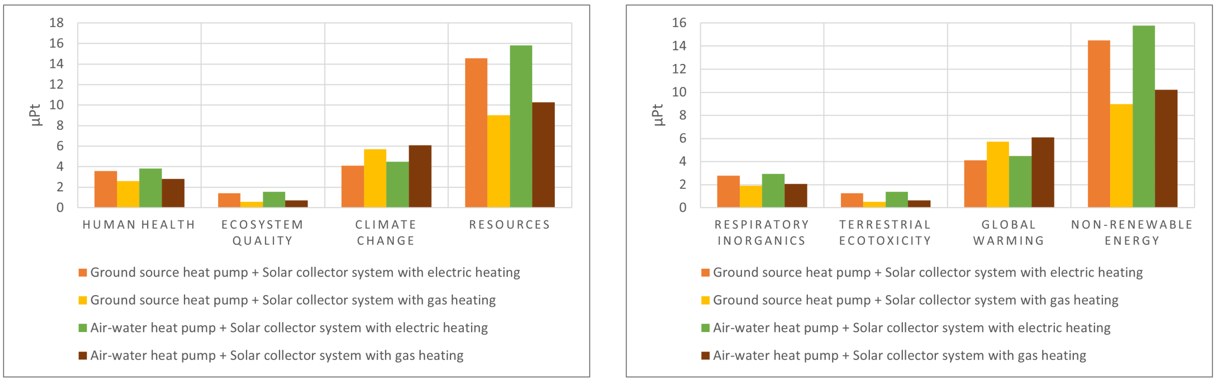


Figure 4.11: Environmental impact scores for different combinations of technologies

any combination with it is disadvantageous compared to the other two combinations. Hence, the two combinations of a heat pump with a solar+electric system score worst environmentally. The two most environmentally friendly combinations are close to each other and are the heat pumps combined with a solar+gas system.

Figure 4.12a shows the underlying damage impact categories, which we will discuss briefly. Based on these damage impact categories, we see relatively low values for 'ecosystem quality' and relatively high values for 'resources' for all combinations. This was similarly the case if we considered each technology separately. The combination ground source heat pump with solar collector system and gas heating comes out best for every indicator except 'climate change'. For this indicator this combination is even second worst. The air-water heat pump combined with solar+gas is considered the second best combination in terms of environmental impact. The difference between these two most environmentally friendly combinations is even fairly small and almost entirely due to a difference in 'non-renewable energy'.



(a) Environmental impact scores per damage category

(b) Environmental impact scores per relevant midpoint category

Figure 4.12: Environmental impact scores per endpoint/midpoint category for different combinations of technologies

Figure 4.12b shows the values for the relevant midpoint categories. By relevant we mean the categories where the environmental impact for the category of at least one combination makes up 5% of the total environmental score of the corresponding combination. This graph shows similar results as the damage impact categories since each time there is one midpoint indicator per cluster that is relevant (makes up more than 5% of the total environmental score). With these findings, we conclude our analysis of the environmental impact scores of both individual technologies and combinations of technologies. Our main findings are discussed in the next section.

4.4 Conclusion

This descriptive LCA analysis yields a number of interesting conclusions, which we will now briefly discuss. These conclusions depend on our methodology and the assumptions we explained earlier.

First of all, we can conclude that heat pumps score significantly better on all environmental impact indicators compared to the investigated solar thermal systems. The ground source heat pump (5.97 µPt) has the lowest environmental impact score shortly followed by the air-water heat pump (7.97 µPt) and in third place the solar+gas system (17.70 µPt). Especially the solar collector system with electric heating has a very high environmental impact of 17.70 µPt compared to the other heat production technologies.

Second, we also examined combinations of two technologies from a different cluster. This proved that the ground source heat pump combined with the solar collector system with gas heating is the most environmentally friendly option, shortly followed by the air-water heat pump also combined with the solar collector system with gas heating. The combinations with solar+electric have worse environmental impact scores.

Third, we also observed throughout the analysis that both clusters of technologies, i.e. both heat pumps and solar thermal systems, show similar peaks for damage and midpoint impact indicators. In each case, significant values recur for the midpoint impact categories of 'non-renewable energy', 'global warming', 'respiratory inorganics' and 'terrestrial ecotoxicity'. In terms of endpoint impact indicators, the 'resources' category often has higher values, unlike the 'ecosystem quality' category which often has lower values.

What we now remember for our analysis in Chapter 5 are mainly the overall environmental impact scores. For the individual technologies aimed at heat production, the range of environmental impact scores is from rounded 6 µPt to 18 µPt. For the combinations of heat production technologies, the range of environmental impact scores is from rounded 18 µPt to 26 µPt. Our analysis showed that the same indicators tend to peak over and over again, and therefore determine the overall environmental impact score. Hence, from this point on, we will abstract from the underlying endpoint (damage) or even midpoint impact indicators and assume that these overall environmental impact scores are sufficiently informative.

5

Analysis and Results on Integrating Environmental Impacts into Project Management

In this chapter, we aim to integrate environmental impact scores into construction project management. To tackle this in an orderly manner, we start by explaining a general framework. This framework demonstrates the structure that we will afterwards apply to an actual case study. The case study we will examine is regarding the construction of an industrial complex with a production hall, storage space, blast cabin, various offices and so on. We will focus in this case study on the work packages or activities that produce heat. This allows us to integrate the results of Chapter 4 during our analysis to incorporate sustainability into the project.

The steps of the framework will be applied to the plan phase of the case study. It will then also be linked to the data that was available after the project's execution. This is necessary because the planning phase is not necessarily accurate in terms of predicting durations, costs and so on. Unfortunately, actual data for environmental impact scores is not yet available for the industrial complex project we will investigate.

However, we realise that our analysis entails some limitations. We will also discuss these. Nevertheless, to verify certain assumptions and decisions of our analysis, we will perform a sensitivity analysis to check the robustness of the results. After performing the sensitivity analysis, we will also apply the framework to a second case study which will allow us to verify the validity of our results to some extent.

5.1 Framework

In what follows, we will explain the framework which is visually depicted in Figure 5.1. The framework consists of six steps, including first three selection steps. This is followed by the calculation of the environmental impact scores that we discussed in the previous chapter. These environmental impact scores can be linked to the selected work packages and activities. Subsequently we calculate e-scores based on the environmental impact scores and we discuss some possibilities regarding their progression over time. The six steps are explained in more detail below.

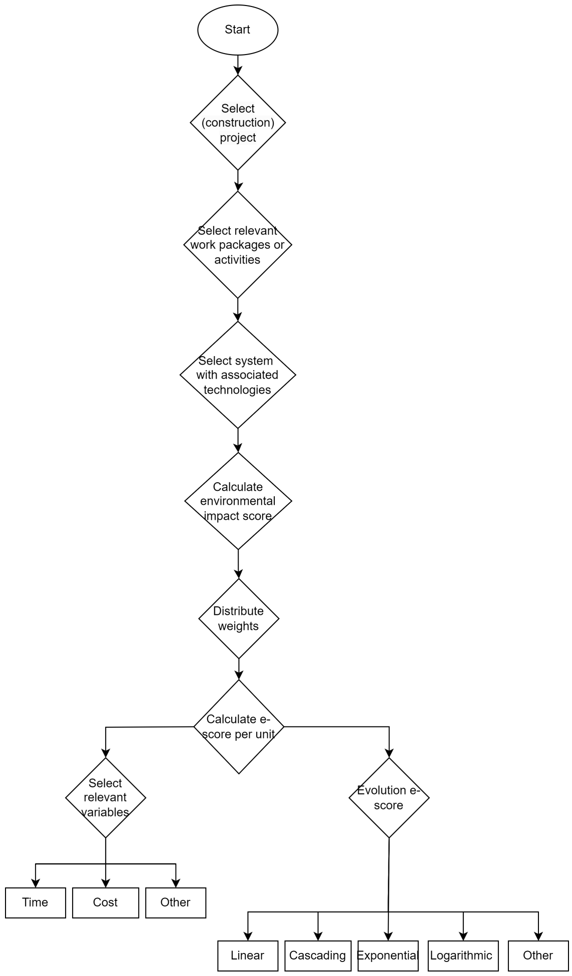


Figure 5.1: Framework to integrate environmental impact scores into construction projects

1. The framework starts with the selection of the (construction) project in which the scope is well defined. For the environmental impact calculations, it is also extremely important to define the scope, which consequently also applies to the project.

2. Secondly, the relevant work packages or activities can be selected to focus on. In the case of projects with a very small scope, the entire project can be considered as a whole, but usually it is recommended to focus on certain parts and then bring everything together.

3. This is followed by the selection of the possible technologies or clusters of technologies. Ideally, systems are created with an ideal scope corresponding to the scope of the selected work packages or activities. In addition to technologies, these systems include resources, support processes and disposal processes that enable this system to perform the function of the relevant work packages or activities. Creating systems as opposed to considering the technologies in isolation is crucial because the added resources and processes also affect the environment.

4. In this step, the environmental impact scores are calculated, which we have already discussed in the previous chap-

ter. This score could possibly be further divided into underlying damage or even midpoint impact indicators. When analysing the impact indicators in Chapter 4, we found that often the same indicators tend to peak and consequently determine the overall environmental impact score. If this is the case for multiple systems in a project, the single score may be sufficiently valuable. However, in case of large differences between damage or midpoint impact indicators of different systems in the same project, it is recommended to be particularly careful. A subdivision of the single score into key impact indicators may then be an option to incorporate into the project data.

5. For each relevant work package or activity, weights can be distributed according to their contribution to the system's environmental impact score. Subsequently, these weights can be multiplied by the calculated environmental impact scores.

6. From now on, we use 'e-scores' which are calculated based on the environmental impact scores. Furthermore, this step includes some crucial decisions that need to be made to arrive at the e-score per unit. On the one hand, the relevant variables have to be selected, which means making it time or cost specific. If we make the e-score time specific, we express the e-score per time unit. On the other hand, it is important to determine the evolution of the e-score. Both the relevant variables and the evolution of the e-score may vary depending on the project or the function of the system under investigation. To clarify this, we will use some examples.

   - In the case of a large office and industrial site with solar panels on the roofs all over the place, a **linear** evolution may be a justified choice. The more solar panels are installed, the more value they add to electricity generation activities. Meanwhile, the environmental impact also increases with the number of solar panels installed.
   - In contrast, for wind turbines, a better scenario is one where the environmental impact score is earned only **at the end** of the work package or activity. The installation of a wind turbine can take a relatively long time, and although the environmental impact increases throughout this time, it is only after the installation that the technology becomes useful for the project. Half a wind turbine is not yet capable of generating any energy. In the case of multiple wind turbines, a **cascade** evolution can be applied in which a step is taken after each installation of one wind turbine.
   - In some cases, **exponential** evolution may be appropriate. An example would be work packages or activities that include isolation work. The more places in the building that are insulated, the greater the effect. However, if one place were not yet insulated, thermal bridges or draft holes could occur. Hence, linear evolution is less appropriate in this case. In contrast, an exponential evolution better reflects the evolution of the e-score.

Consequently, based on all the aforementioned steps, an e-score per unit of time or cost can be calculated for each work package or activity considered. This can be taken into account along with the other project data and potentially influence the decisions of the project teams. As a result, other technologies/systems may be chosen that emerge best when all criteria, including sustainability, are considered.

Having fully explained the framework, we will now apply it to a case study in the construction sector. In doing so, we will rely on the results concerning the environmental impact scores of Chapter 4. Similarly, we will explore eight alternatives, including four single technologies and four combinations of technologies. We will carry out the final steps of the framework separately for these alternatives.

5.2 Case Study

The first project we will examine is about an industrial complex. The project data is taken from the DSLIB dataset from the OR&S project data webpage (OR&S, 2015). The project, named "Industrial Complex (2)" can be found in the construction (industrial) sector and has ID 63 and code C2015-07. The project ranges from demolition works to building and finishing a complete industrial complex with production hall, storage space, blast cabin and offices. Furthermore, there is a floor 0 and +1 and there are also environmental works, such as loading dock, dock leveller and exterior landscaping. As in Chapter 4, we continue to focus on work packages or activities with the aim of heat production.

First, we consider the planning phase, predicting a certain duration and cost for each heating activity. In addition, we also predict an e-score per heating activity. For this, we will work out a number of scenarios, as explained in the framework. Afterwards, we will also take the data into account regarding the actual execution to observe the differences between plan and execution.

5.2.1 Plan

According to the predetermined basic schedule, the duration of the project was estimated at about 14 months from 18 February 2013 to 8 April 2014. Taking into account weekends, this would amount to 297 working days. In this project, we focus on the work packages or activities aimed at heat production. The earliest heating activities are planned from 24 June 2013 as preparatory works and foundation works, among others, need to be done first. The heating activities are divided under different work packages, such as techniques in the production hall, storage space and blast cabin. In addition, we also consider the HVAC work package, which consists of activities concerning pipes in floors, walls and ceilings. HVAC is the abbreviation for Heating, Ventilation, and Air Conditioning. From now on, we will use heating activities interchangeably with HVAC activities. The baseline schedule for the relevant activities, namely the heating activities, is shown in Figure 5.2.

Besides the duration time, costs were also predicted for the heating activities. Fixed costs were 0 € in each case and variable costs were based on 720 €/hour for all heating activities. For other activities, these predicted costs per hour varied widely. To calculate a baseline total cost per heating activity, we multiply 720 €/hour by the number of expected working hours on the activity. Table 5.1 gives a clear overview of the activity with the work package it belongs to as well as the baseline duration and baseline total cost.

In summary, we have already completed the first four steps of the framework. The project we are investigating is the construction of an industrial complex (step 1). The work packages and activities we specifically investigate concern HVAC (step 2). Steps 3 and 4 of the framework have already been covered in Chapter 4. The technologies we are investigating for the selected activities and work package are a ground source heat pump, an air-water heat pump, a solar powered system

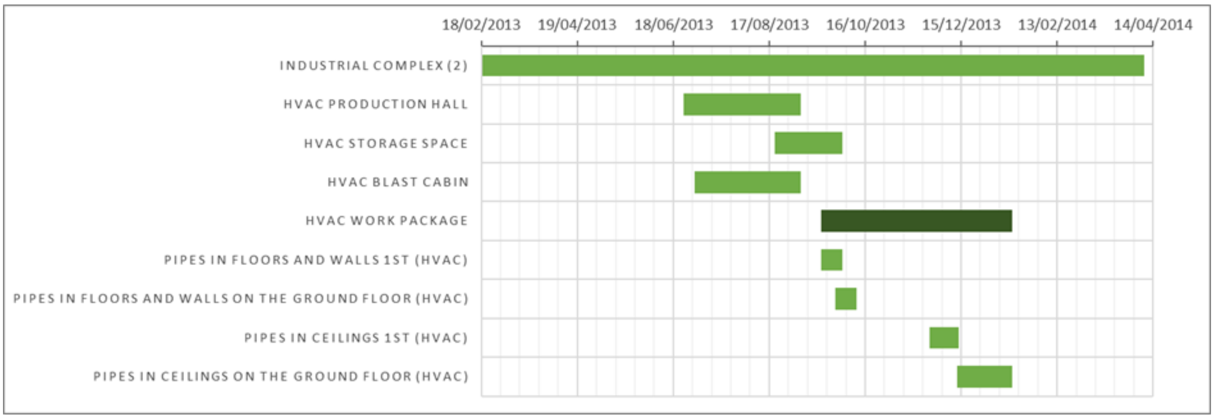


Figure 5.2: Baseline schedule of HVAC activities for industrial complex project

ID	WP / A	Name activity	Accompanying work package	Baseline duration	Baseline total cost
35	A	HVAC	Techniques production hall	54d	311 040.00 €
56	A	HVAC	Techniques storage space	31d	178 560.00 €
75	A	HVAC	Techniques blast cabin	49	282 240.00 €
147	WP	HVAC	HVAC	86d	345 600.00 €
143	A	Pipes in floors and walls 1st	HVAC	10d	57 600.00 €
144	A	Pipes in floors and walls on the ground floor	HVAC	10d	57 600.00 €
145	A	Pipes in ceilings 1st	HVAC	15d	86 400.00 €
146	A	Pipes in ceilings on the ground floor	HVAC	25d	144 000.00 €

Table 5.1: Heating activities of industrial complex project

with electric auxiliary heating and one with gas auxiliary heating. Their environmental impact scores are 5.97 μPt, 7.97 μPt, 17.70 μPt and 11.94 μPt, respectively. In addition, we also explore four combinations, namely ground source heat pump + solar collector system with electric heating (23.67 μPt), ground source heat pump + solar collector system with gas heating (17.91 μPt), air-water heat pump + solar collector system with electric heating (25.67 μPt) and air-water heat pump + solar collector system with gas heating (19.91 μPt). The next and therefore fifth step of the framework is the distribution of the contribution of an activity to the overall environmental impact score of the corresponding technology. Here, each HVAC activity is given a weight and the sum of the weights of all these HVAC activities is 100%. We will discuss this fifth step in more detail in the next section.

Distributing weights

We start our analysis by using one single technology, namely the **ground source heat pump**. We assume that the ground source heat pump has enough capacity to heat and cool the three places, which are the production hall, stock room and blast cabin. Our first major decision to make at this point is the weights we give to each activity. This means that the total environmental score of 5.97 μPt generated by the heat pump is not entirely charged to one activity, but each activity contributes to it.

For the three spaces, we can assume that they each account for one-third of the total environmental score of the heat pump. However, it is important to mention that we do not have information on the size of the rooms, the degree of insulation of the room, the heat required etc. With this information, the weights would probably be different. If we take into account the expected durations and costs of the first three heating activities, we notice relatively large discrepancies between them. As a result, there is a suspicion that the weights of 33.33% are not entirely correct. Consequently, a sensitivity analysis of these weights on the final solutions could be very interesting. In addition, we must also take into account the piping in floors, walls and ceilings. To make a reasoned assumption, we use life cycle analysis studies from the literature where we can find out to what extent the piping contributes to the total environmental score of the heat pump.

Evidence from various literature studies shows that the piping network is a relatively small contributor to the environmental score of heat pumps (Bonamente & Aquino, 2020; Blom et al., 2010; Vu et al., 2013). Greening & Azapagic (2012) examined the impact of different parts of the life cycle. This showed that the largest contributor to most impacts of heat pumps is operation, which contributes an average of 84% to the total, mainly due to electricity consumption. Raw material production contributes about 10%, while maintenance, disposal and transportation are comparatively low contributors. The only exception is 'Ozone Layer Depletion Potential', of which the most is caused by chlorinated emissions in the production of the refrigerant. Consequently, the overall environmental score is mainly determined by the electricity required for operation, the high material content of the system and the refrigerant used (Blom et al., 2010; Saner et al., 2010). The refrigerant is a liquid specifically designed to transport heat, which is why we include it in the weights of the pipes in the floors, walls and ceilings (Yan & Lin, 1999).

We assume that these pipes for HVAC contribute 10% relative to the total environmental impact score of the ground source heat pump. To make the specific breakdown by activity, we use the relative cost of the activity to the total HVAC work package. Taking this into account in conjunction with the assumption to give the three spaces, namely production hall, storage space and blast cabin, one-third of the remaining weight each, we obtain the weights shown in table 5.2. To calculate the absolute weights, we applied the relative weights to the results of previous chapter.

It is worth emphasising that these weights are case-specific and based on assumptions. Up to now, we have distributed the weights for the activities in the case of the ground source heat pump. When comparing several individual technologies, combinations of technologies or even systems, the weights for the activities may differ depending on the type of activity. Imagine that the heating activities were divided into the production of the heating technology, the use phase and the disposal phase. In this case, different technologies or systems would probably lead to different weights for these activities. For example, certain technologies have limited environmental impact during use and can be recycled afterwards, but require many raw materials that are difficult to mine, making production highly polluting. This contrasts with other technologies. In what follows, we will extend the reasoning of distributing weights for the total environmental impact score of the ground source heat pump to the other three individual technologies. Subsequently, we can do a similar approach for combinations of technologies.

Since the **air-water heat pump** has similar contributors compared to the geothermal heat pump for many effects, it seems reasonable to us to apply the same weights for it. Similarly for **solar heating technologies**, we find that the use phase (and thus electricity) is the largest contributor to the overall environmental score for the technology in consideration (Beccali et al., 2012; Herrando et al., 2022). In this cluster of technologies, we also notice a relatively large contribution from solar collectors (Souliotis et al., 2018). As a result, we similarly conclude for solar heating technologies that the piping network in floors, walls and ceilings contributes a relatively small proportion relative to the total environmental score for the technology. For this reason, we apply the same relative weights to the activities for each individual technology. In table 5.2, we show the environmental impact score for each activity based on the relative percentage of the technology's environmental score.

				Absolute weights			
ID	**WP / A**	**Name activity + Accompanying work package**	**Relative weights**	**Ground source heat pump**	**Air-water heat pump**	**Solar + electric**	**Solar + gas**
35	A	HVAC Techniques production hall	30%	1.791	2.391	5.310	3.583
56	A	HVAC Techniques storage space	30%	1.791	2.391	5.310	3.583
75	A	HVAC Techniques blast cabin	30%	1.791	2.391	5.310	3.583
147	WP	HVAC	10%	0.597	0.797	1.770	1.194
143	A	Pipes in floors and walls 1st (HVAC)	1.67%	0.099	0.133	0.295	0.199
144	A	Pipes in floors and walls on the ground floor (HVAC)	1.67%	0.099	0.133	0.295	0.199
145	A	Pipes in ceilings 1st (HVAC)	2.50%	0.149	0.199	0.443	0.299
146	A	Pipes in ceilings on the ground floor (HVAC)	4.17%	0.249	0.332	0.738	0.498

Table 5.2: Absolute weights of the environmental impact score of single technologies for different heating activities for industrial complex

If we now extrapolate this reasoning to the choice of weights in case we combine two technologies, we get the results depicted in Table 5.3. The relative percentages of how much an activity contributes to the overall impact score are not affected. What does vary is the environmental impact score by which these percentages are multiplied. For this we use the results of Figure 4.11 from Chapter 4.

				Absolute weights			
ID	**WP / A**	**Name activity + Accompanying work package**	**Relative weights**	**Ground source heat pump + Solar collector system with electric heating**	**Ground source heat pump + Solar collector system with gas heating**	**Air-water heat pump + Solar collector system with electric heating**	**Air-water heat pump + Solar collector system with gas heating**
35	A	HVAC Techniques production hall	30%	7.101	5.627	7.702	6.228
56	A	HVAC Techniques storage space	30%	7.101	5.627	7.702	6.228
75	A	HVAC Techniques blast cabin	30%	7.101	5.627	7.702	6.228
147	WP	HVAC	10%	2.367	1.876	2.567	2.076
143	A	Pipes in floors and walls 1st (HVAC)	1.67%	0.395	0.313	0.428	0.346
144	A	Pipes in floors and walls on the ground floor (HVAC)	1.67%	0.395	0.313	0.428	0.346
145	A	Pipes in ceilings 1st (HVAC)	2.50%	0.592	0.469	0.642	0.519
146	A	Pipes in ceilings on the ground floor (HVAC)	4.17%	0.986	0.782	1.070	0.865

Table 5.3: Absolute weights of the environmental impact score of four different technologies for different heating activities for industrial complex

Once the weights for the different relevant work packages and/or activities are distributed, we can move on to the next step in the framework. In this step, we will move from environmental impact scores to e-scores and explore some scenarios regarding for their possible progression. We will explore these scenarios for both single technologies and combinations of technologies.

Evolution e-score

Until now, we wanted the total environmental impact scores to be as low as possible. To make the next steps in the analysis more comprehensible, we raise the environmental scores per activity to the -1st power[1]. This ensures that the minimisation problem becomes a maximisation problem. For the sake of clarity, we call the impact scores to the negative first power "**e-scores**", where we want to achieve the highest e-score possible.

In this section, we address the question of how the e-score evolves if we implement the considered technology in the project. This will require us to decide, on the one hand, if the e-score is time- or cost-specific and, on the other hand, if the evolution is linear, cascading, only at the end or in any other way. Each choice has its advantages and disadvantages, which is why we work with scenarios. Currently, we limit ourselves to these possibilities, but other scenarios such as exponential or root functions may be more suitable in some cases.

To be clear, the different scenarios do not affect the total e-score for each technology. What does differ is how the e-score is earned throughout the activities of that specific technology. For each scenario we examine, the HVAC activities all have the same type of evolution. Suppose we work out the scenario time - linear, then for each activity for the particular technology under consideration there is a linear evolution of the e-score.

As in step 4, the calculation the environmental scores, and step 5, the distribution of weights for the relevant work packages and activities, we will again consider the eight possible options, namely the four single technologies and the four combinations of technologies. First, we will examine the evolution of e-scores for single technologies. In this context, the scenarios are more suitable where the evolution is linear or where the e-score is earned at the end of the activity. Second, we will examine the case of combined technologies where the scenarios of linear evolution and cascading evolution of e-scores are more appropriate.

Single technology

First, we consider the four single technologies as options to be implemented in the industrial complex project. In this case we consider multiple settings, namely involving time and/or cost. We also distinguish between a linear evolution of the e-score and an evolution where the e-score is taken into account at the end of the activity. Consequently, in the case of single technologies, we examine four scenarios.

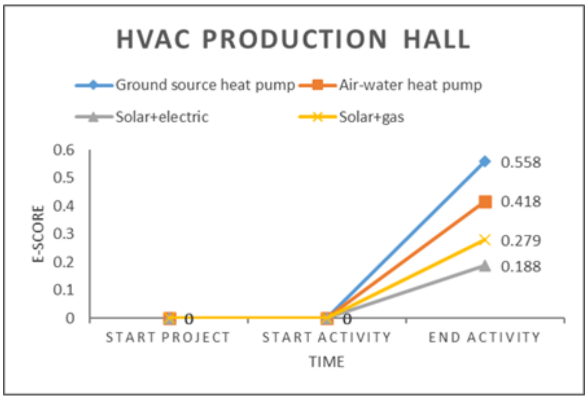
Opting for a linear evolution of an e-score or an e-score earned at the end depends on the activity and certain assumptions. Imagine the case where the wells have already been drilled for the geothermal heat pump, but the underfloor heating has not yet been connected. In this case, this technology does not yet deliver any benefit. However, the drilling of the wells

[1] The approach of raising the environmental impact scores to the -1st power, in order to turn a minimisation problem into a maximisation problem, has two detrimental implications. We will briefly mention them here. First, inverting the scores makes it difficult to assess relative environmental impacts, which in turn complicates the comparison and benchmarking of different technologies. Second, the environmental impact scores can be disaggregated into multiple endpoint and/or midpoint indicators. By inverting the overall environmental impact score, the weighting of each impact category relative to the overall impact score is different, which can lead to confusion. For our analysis, we only consider the overall environmental impact score and not the underlying impact categories.

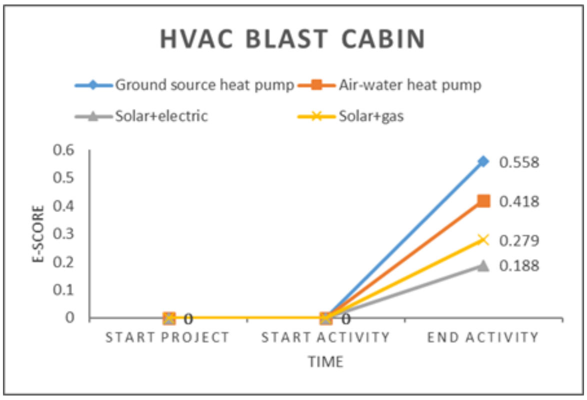
already has an impact on the environment, such as the fuel for the geothermal drilling rig, the impact on the soil, the pipes that are inserted into the wells and so on. Opting for a linear evolution of the e-score would be a potentially valid choice since the e-score increases steadily the longer the activity lasts. Alternatively, it would be justifiable for the e-score to be earned at the end of the activity, as it is only at that point that the technology becomes useful to the project. For clarity, these scenarios have no impact on the value of the e-score for the activity, as it remains the same for all scenarios.

In what follows, we will visualise both a linear evolution of the e-score and an e-score earned at the end of an activity. First, we will show both scenarios for one activity taking abstraction from all other activities. Hence, we will consider the activities in isolation from each other. Afterwards, we will observe e-scores over the duration of the project taking into account all HVAC activities. This means that if several HVAC activities are performed in parallel on a given day, the sum of the e-scores of all HVAC activities on that day is taken into account.

Scenario time – linear We will first consider a linear evolution of an activity independent of the other activities. HVAC Production hall starts at e-score 0, because this is the first heating-related activity in the project. This activity was scheduled to start on 24 June 2013. An observation of the Gantt chart in Figure 5.1 shows us that the HVAC blast cabin activity starts 7 days later than the HVAC production hall according to the baseline schedule. Both activities are then performed in parallel. From 20 August 2013, the HVAC activity for the storage space starts. From then on, these three HVAC activities are performed in parallel until September 5, 2013, because then the HVAC activities in the production hall and in the blast cabin are completed according to the baseline schedule. We can complete this reasoning for the activities related to the piping network in floors, walls and ceilings on the ground and first floor. To structure our analysis, we start by plotting the first two activities separately relative to time. This results in the two graphs depicted in Figure 5.3.



(a) Evolution of e-score for HVAC activity in production hall independent of other activities



(b) Evolution e-score for HVAC activity in blast cabin independent of other activities

Figure 5.3: Evolution of e-score as a function of time for two HVAC activities if independent of each other

Scenario time – end result We now consider an activity in isolation where the e-score is only earned at the end of the activity. For the HVAC activity in the production hall, the evolution of the e-score is shown in Figure 5.4. The other heating activities are similar, making it unnecessary to show them as well. Both before the activity and during the activity, the e-score remains at zero. Only at the end of the activity is there a peak where all the e-score is earned. After the activity, the e-score remains at the same level if we abstract from other activities in the project that also generate e-scores.

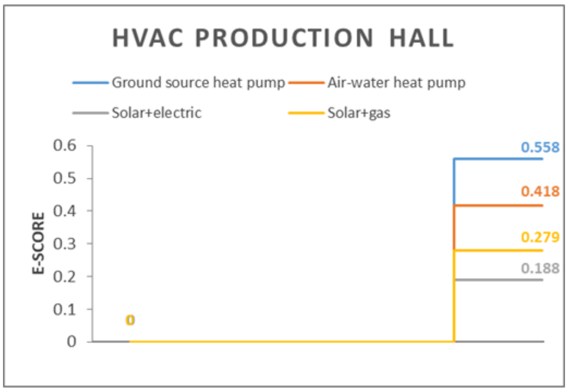
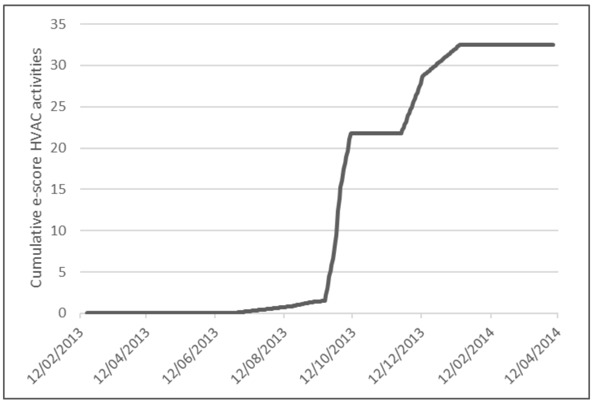
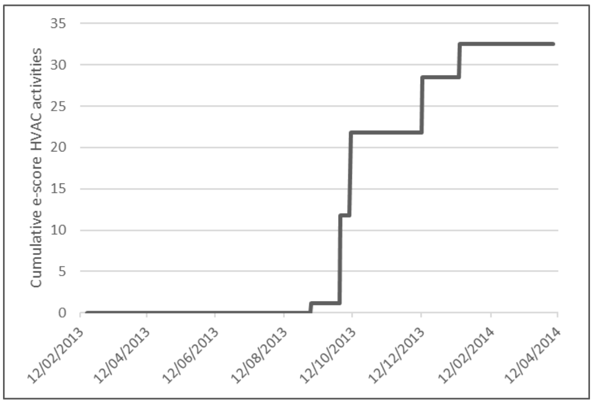


Figure 5.4: Evolution of e-score as a function of time for HVAC activity in production hall independent of other activities

Subsequently, we integrate these separate, independent graphs into one graph that includes all HVAC activities such that the relevant e-scores add up when activities are performed in parallel. For simplicity, we make abstraction of weekends and holidays and examine the evolution of e-scores in calendar days rather than merely working days. Figure 5.5 shows the evolution of the e-score for the time - linear and time - end result scenarios for the ground source heat pump. We notice a similar evolution between the two scenarios. The HVAC activities are relatively short compared to the total duration of the project, so the linear evolution increases quite rapidly. All seven HVAC activities we consider for this project are included in the figure. Certain HVAC activities have the same end date according to the baseline schedule. This means that the e-scores of these activities are earned at the same time in the time - end result scenario. This is the case for the activities HVAC production hall and HVAC blast cabin, as well as for the activities HVAC storage space and pipework in floors and walls on the first floor. Hence, on the graph of time - end result, we see only five steps instead of seven.



(a) Scenario time - linear



(b) Scenario time - end result

Figure 5.5: Evolution of e-score for scenarios time - linear and time - end result for ground source heat pump

For project teams, it would be interesting if these figures were available for different technologies. In Figures 5.6 and 5.7, we provide a visual summary for the single technologies we discussed and analysed in Chapter 4. These figures plot the cumulative e-score for the time - linear and the time - end result scenario, respectively. Based on these figures, we can conclude that the ground source heat pump outperforms the other single technologies in terms of environmental impact at all times. Solar+electric appears to be the least environmentally friendly technology. Hence, by abstracting costs, delivery times, supplier relationships, etc., project managers can easily make their decision for a particular technology suitable for HVAC activities. Based on environmental impact, it is evident that they would opt for ground source heat pumps. This applies to both the time - linear and time - end result scenarios.

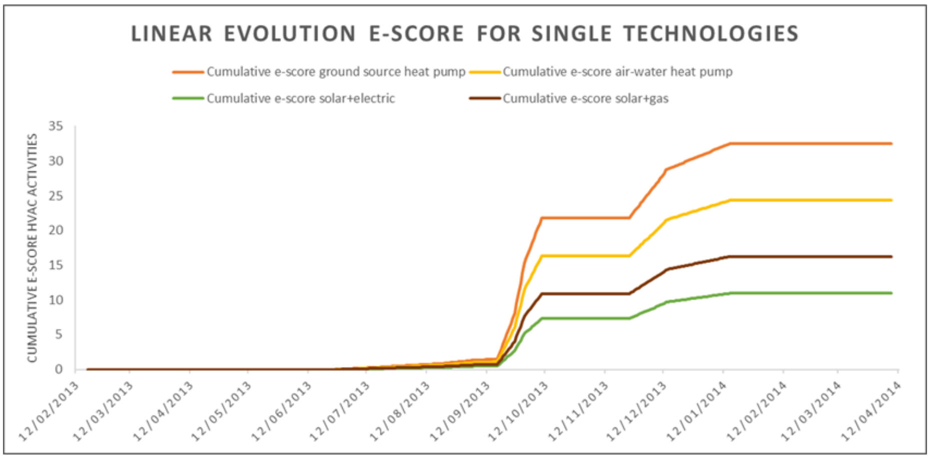


Figure 5.6: Linear evolution of cumulative e-scores for all four technologies

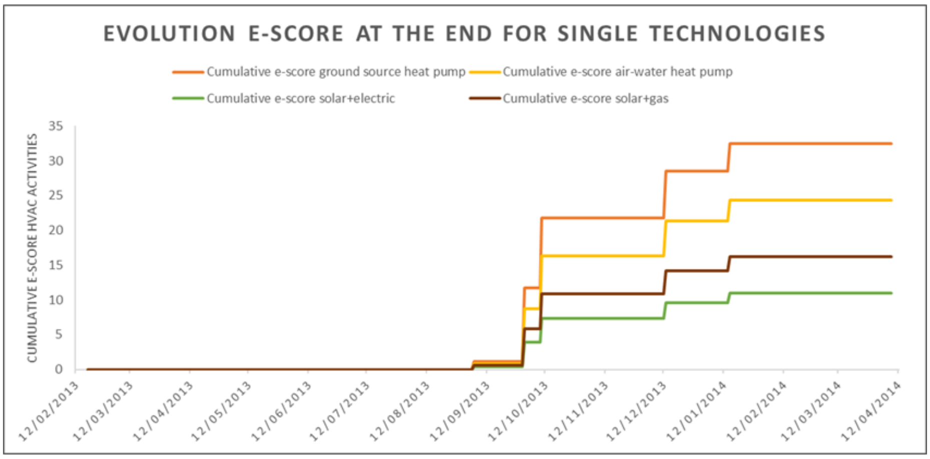


Figure 5.7: Evolution of cumulative e-scores earned at the end of each HVAC activity for all four technologies

However, this conclusion can be nuanced if we consider the bigger picture. For a meaningful assessment, we should regard these environmental scores relatively to the entire project and its encompassed activities. For example, it may be that relatively speaking, the differences between these four technologies are so small that the decision depends on other factors such as cost, delivery time, efficiency, etc.

Having clarified the two scenarios where we only include time, we move on to the next two scenarios where we will also include cost. As with the previous scenarios, we provisionally consider only individual technologies for these next two scenarios.

Scenario time & cost – linear From this point on, we will also include cost trends in our charts. In order to compare e-scores with costs, where both are plotted as a function of time, we normalise the e-scores by technology. We had already taken the absolute weights from Table 5.2 to the negative first power to obtain a maximisation problem. Hence, if we normalise these weights by technology, we get the results shown in Table 5.4. Since the weights per activity are identical for the different technologies, the normalised values per activity are also identical for the different technologies.

				Absolute weights			
ID	**WP / A**	**Name activity + Accompanying work package**	**Relative weights**	**Ground source heat pump**	**Air-water heat pump**	**Solar + electric**	**Solar + gas**
35	A	HVAC Production hall	30%	0.017	0.017	0.017	0.017
56	A	HVAC Storage space	30%	0.017	0.017	0.017	0.017
75	A	HVAC Blast cabin	30%	0.017	0.017	0.017	0.017
143	A	Pipes in floors and walls 1st (HVAC)	1.67%	0.309	0.309	0.309	0.309
144	A	Pipes in floors and walls on the ground floor (HVAC)	1.67%	0.309	0.309	0.309	0.309
145	A	Pipes in ceilings 1st (HVAC)	2.50%	0.206	0.206	0.206	0.206
146	A	Pipes in ceilings on the ground floor (HVAC)	4.17%	0.124	0.124	0.124	0.124
Sum				**1.000**	**1.000**	**1.000**	**1.000**

Table 5.4: Absolute normalised weights of the environmental impact score of four different technologies for different heating activities for industrial complex

To obtain a smooth evolution of both normalised e-scores and normalised costs as a function of time, we take abstraction of weekends and holidays. During the activity, costs and e-scores increase per calendar day and therefore both during weekdays, weekends and holidays. To be clear, this does not change the costs and e-scores, but rather smooths the graph. Fixed costs were 0 € in each case and variable costs were based on 720 €/hour for all HVAC activities. During the project, the working days were eight hours per day. Consequently, we multiply the cost per hour by eight hours and by the number of expected working days per activity.

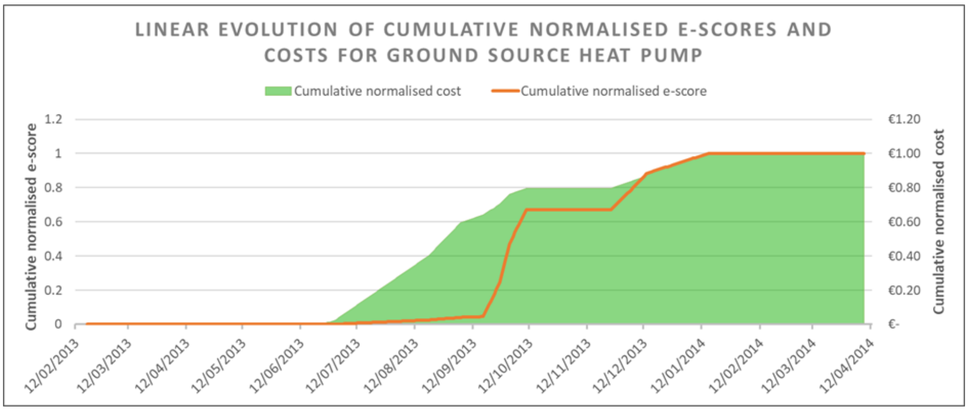


Figure 5.8: Linear evolution of cumulative normalised e-scores and costs for ground source heat pump

Figure 5.8 shows a graph where cumulative normalised costs and cumulative normalised e-scores are plotted as a function of time in the case of a ground source heat pump. We got similar conclusions for the other single technologies, which is why we do not show them here. The project is expected to start on 18 February 2013 according to the baseline schedule. In fact, we can divide this graph into three sections, each with different dynamics of e-score compared to cost. The first HVAC activity will start on 24 June 2013 and it will take place in the production hall. From the start of the first HVAC activity, we notice large investments but only little contribution by e-score. Subsequently, we observe a second section where there is a huge peak in terms of e-score, while costs continue to rise fairly steadily. After the peak, we get both a flat e-score and cost. In this third section, the e-score and cost converge and evolve equally. The end of the last HVAC activity is scheduled for 15 January 2014. This means we will not have any changes in e-scores or costs for HVAC activities after this date. This will be followed by painting, clean-up and other activities and the project is expected to finish on 8 April 2014. This chart is sensitive to a number of assumptions we made. To check the robustness of the results, we will change the weights of the HVAC activities in subsection 5.2.4. Based on those results, we can recreate this graph and assess the extent to which its conclusions have changed drastically or not.

Scenario time & cost – end result In this scenario, we no longer have a linear evolution of e-scores, but the e-score is earned at the end of the activity. Costs continue to increase daily as in the previous scenario. Figure 5.9 shows the graph of cumulative normalised e-scores and cumulative normalised costs as a function of time. Also in this scenario, we only show the graph for the ground source heat pump, as the conclusions for the other single technologies are not significantly different. In this chart, the three sections are less clearly visible. For instance, equalisation in the third section is less visible. Only after the last HVAC activity and hence after 15 January 2014 e-scores and costs start to equalise. Other differences with Figure 5.8, which depicts the time & cost - linear scenario, are quite small as the duration of the HVAC activities are relatively small compared to the project.

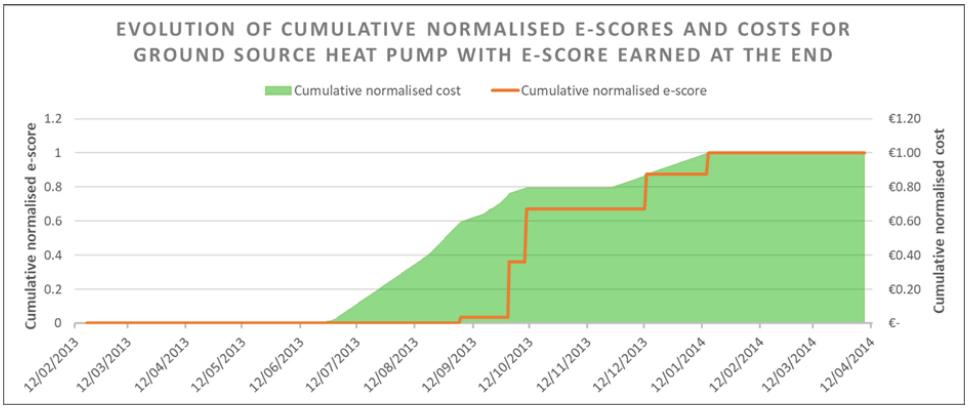


Figure 5.9: Evolution of cumulative normalised e-scores and costs for ground source heat pump with e-score earned at the end

Up to this point, we examined four scenarios of how the e-score might evolve over time for the individual technologies. Since we are applying the framework in Figure 5.1 to both four individual technologies and four combinations of technologies, we will also perform the last step of the framework for combinations of technologies. In the next section, we will explore some scenarios with different e-score curves for combinations of technologies.

Combined technologies

In some cases, it may be necessary to combine multiple technologies for certain activities. We still consider the HVAC activities in the industrial complex project. Possibilities for heat production include combinations of the four technologies already investigated, namely ground source heat pumps, air-water heat pumps, solar collector systems with electric heating on the one hand or combined with gas heating on the other. As in Chapter 4, we consider the combinations of two technologies providing heating from a different cluster each time. Our descriptive analysis in Chapter 4 resulted in environmental impact scores for the combinations between 19 μPt and 25 μPt. As already mentioned, these values are case-specific and based on assumptions. For other technologies, it is therefore possible that these values may differ and fall outside this range.

Similar to how we explored some scenarios of possible e-score evolution for single technologies in the last step of the framework, we also do a similar exercise for combinations of technologies. Similarly, we will consider the progression of the e-score over time with only time included on the one hand and both time and cost included on the other. For each, we consider the difference between linear growth and cascading growth. This enables us to explore four scenarios as well.

The motivation for linear evolution remains unchanged than in the case of single technologies. In the case of combined technologies, we no longer find it appropriate to investigate a scenario where the e-score is only earned at the end of the activity. More preferable is to investigate a cascading evolution. After installing one technology, we can assume that the corresponding e-score for that one technology is earned. Afterwards, the second technology is installed and at the end of it, the e-score of that second technology can also be added. Basically, this is the extrapolated version of the scenario of single technologies where we assumed that the e-score is earned at the end of the activity.

With this analysis of combined technologies, we aim to show that the methodology can be extended from one technology per activity (or activities) to multiple technologies. We therefore apply similar calculations but work with a different and higher range of environmental impact scores and assess different scenarios. Extending our analysis to multiple technologies is a useful step towards a whole-building environmental analysis. However, this will require revisiting some limitations. As in Chapter 4, we do not yet take interactions between the various technologies into account. For instance, the degree of insulation of the building envelope has a major influence on the efficiency and energy use of heat pumps that provide heat. The interactions between different technologies and building design, among others, are necessary to involve in order to obtain a reliable analysis of a building's environmental impact. Consequently, this also has a major impact on the decisions to be made by project managers, real estate managers and other practitioners.

Scenario time – linear First, we consider the linear progression of e-scores as a function of time. Figure 5.10 shows how the e-score for this scenario evolves as a function of time for all four combinations of technologies. The e-scores for the four combinations show a similar trend, but in the end we still notice differences. The most environmentally friendly combination is the geothermal heat pump combined with the solar collector system and gas supplementary heating (solar+gas).

Comparing this graph with the linear scenario of single technologies, we notice a similar evolution of the e-score. However, the daily increments of the e-scores are higher because two technologies are now taken into account. As a result, more resources were mined, more efforts were required for the production and assembly of the technologies and so on. In addition, we observe a smaller range of total environmental impact scores compared to the single technologies. While the environmental impact scores for single technologies are between 6 and 18 μPt, the range for combinations is from 19 to 25 μPt. As a result, the e-score curves for these combinations of technologies are remarkably closer together.

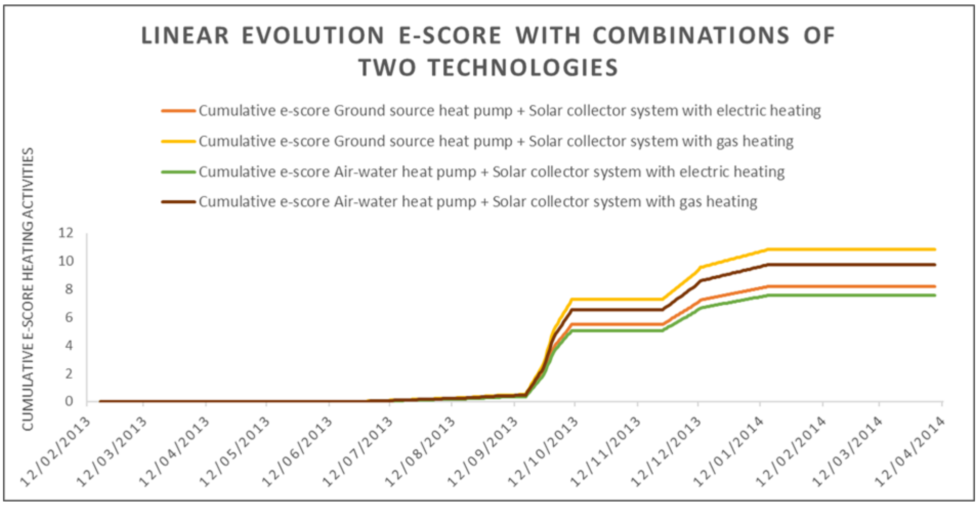


Figure 5.10: Linear evolution of cumulative e-scores for all four combinations of technologies

Scenario time – cascading In the case of a cascading evolution of the e-score, we have to divide HVAC activities into two parts. On average, installing a geothermal heat pump takes more time compared to an air-water heat pump and a solar collector system. We assume that geothermal heat pumps take 60% of the time and solar collector systems with associated auxiliary heating take the remaining 40% of the duration time of HVAC activities. For the combinations with an air-water heat pump, we assume that only 30% of the time of the HVAC activities is spent on the heat pump and the remaining 70% on the solar collector system. Unlike heat pumps, solar-powered technologies need a finished roof to place the solar collectors on. As a result, we assume that the heat pump is always installed first, which means that the e-score of the heat pump is earned first each time. Figure 5.11 shows the cascade evolution as a function of time for all four combinations. We see relatively small increases that follow each other in short succession.

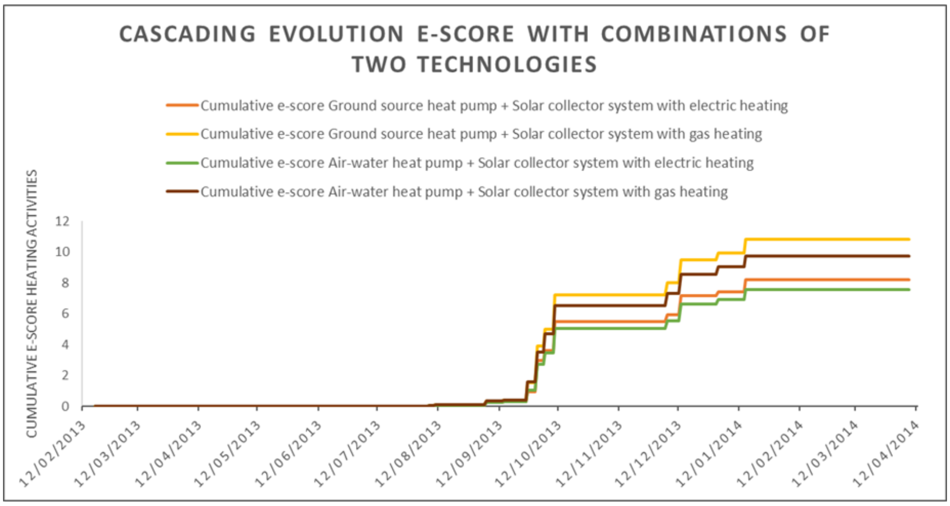


Figure 5.11: Cascading evolution of cumulative e-scores for all four combinations of technologies

Scenarios time & cost As we have done for the single technologies, we also want to examine these scenarios for the combinations of technologies in which we include normalised costs. The weights assigned to the seven HVAC activities remained unchanged. Moreover, we have normalised both e-scores and costs to ensure that they both end up between 0 and 1 and we can compare them in the same graph. As a result, the graph for the time & cost scenario with a linear progression of the e-score is identical to Figure 5.8, where this scenario was examined for single technologies. In addition, the conclusions of the time & cost scenario with a cascading evolution of the e-score for the combinations of technologies are also not significantly different from the conclusions of Figure 5.9, where the e-score was earned at the end of the activity.

The importance of the weights we assigned to the activities at the beginning of the analysis cannot be underestimated. Hence, in section 5.2.4, we will perform a sensitivity analysis where we test a number of scenarios with different weights. In addition, we will also test the validity of the method by applying it to another project within the construction sector. For this second case study, we will also develop some scenarios with different weights for the relevant work packages or activities.

Taking everything together so far, we have gone through all the steps of the framework in Figure 5.1. We have done this with the data from the planning phase. For time and cost, we also have the actual data after the project has been completed. First, we will discuss the differences between the data from the planning phase and the data from the execution phase. Afterwards, we will discuss some limitations and move on to a sensitivity analysis and a second case study.

5.2.2 Execution

Until this point, the calculations were systematically based on the baseline schedule. From this project concerning an industrial complex, we also know the data after project execution. In other words, we know the actual durations and costs. Unfortunately, we do not know the actual e-scores. This section consists of three parts. First, we will examine the extent to which the baseline schedule matches the durations that were effectively required for the activities. Next, we will compare the baseline costs with the exact costs that were needed to complete the activities. Third, we will also try to extrapolate the results of time and cost analyses for the e-score.

Time A visual comparison of the differences in duration time is depicted in Figure 5.12. The baseline schedule is represented by the dark grey bars and the schedule after execution in light green. Consequently, the overlap between the two is shown in dark green. In the beginning, the HVAC activities in the production hall, the storage space and the blast cabin all proceeded on schedule. They all started effectively on the predicted date and also required exactly the number of predicted working days in practice. So until then, there was no delay for HVAC activities.

However, the four activities involving pipe laying were carried out much later than originally predicted. Laying the pipes in the floors and walls started about 6 months later than initially planned. Despite the delay, these activities were executed remarkably faster in practice than expected in advance. While 10 days were scheduled, the works took only 2 days. For the pipes in the ceilings there is a similar story as these two activities, one on the ground floor and one on the first floor, started about two months later than initially planned. These activities were also performed faster than predicted. Both activities were completed in two days, while 15 working days were scheduled for the first floor and even 25 working days for the

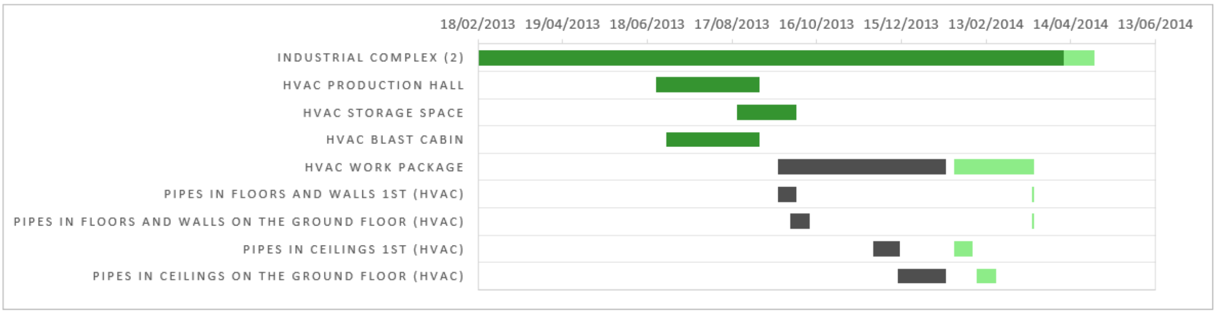


Figure 5.12: Cost comparison of baseline schedule and schedule after execution for HVAC activities

ground floor.

We can therefore conclude that, on average, the HVAC activities did not contribute to the longer duration of the project than predicted in the baseline schedule. In fact, no HVAC activity required more time than planned according to the basic schedule. The entire project lasted 16 working days longer than predicted which is equivalent to three weeks. In terms of time, the extra working days needed to complete the project turned out to be relatively small compared to the overall duration of the project. In what follows, we carry out a similar analysis in terms of costs.

Cost Figure 5.13 illustrates the costs expected according to the baseline schedule compared to the actual costs known after project execution. The conclusions for the cost comparison can largely be linked to the time comparison conclusions. The three HVAC activities for the individual rooms were found to have cost as much as pre-budgeted. This makes sense as these activities also took as long as expected in advance. For the activities involving pipe laying, we notice a lower cost than budgeted beforehand. This can be explained by the shorter working time than expected according to the baseline schedule. As it was the case for time, the differences for the last four activities appear to be relatively large. For this project, only the variable costs per hour are given, which means that the cost per activity is a multiple of the duration of an activity. Consequently, these conclusions would have varied if fixed costs had also been taken into account.

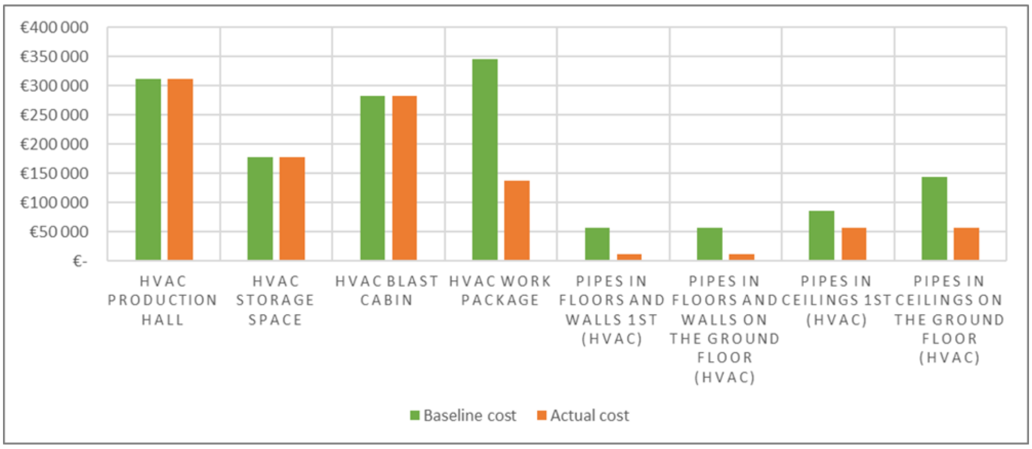


Figure 5.13: Time comparison of baseline schedule and schedule after execution for HVAC activities

E-score Unfortunately, we do not have data on e-scores for this project. Based on previous comparisons for time and cost, we will still include e-scores in our analysis. Actual e-scores can certainly also differ from those expected in advance. For example, costs may differ if more material or energy consumption was needed than expected in advance. These causes not only affect costs, but also e-scores.

Based on Figures 5.12 and 5.13, we noticed that time and cost were linked, partly because only the variable cost was taken into account. In contrast, for e-scores, we suspect this may not be the case. Our literature review showed that especially the operation of certain technologies has a major impact on the environmental impact of the technology and consequently on the building. This bears little relation to both time and staff costs. In contrast to time and cost, it is also difficult or even impossible to reflect actual e-scores. Until now, e-scores in our analysis have been determined using assumptions and data sourced from databases. This is not possible in order to arrive at actual values.

While we have gained some interesting insights until this point, we are aware that our framework and analysis has some limitations. We will discuss these in the next section. Subsequently, we extend our analysis with a sensitivity analysis and a validity check. This allows us to verify the robustness of the results and assess the effect when we apply the framework to another case study.

5.2.3 Limitations

Our analysis may already be a step in the right direction towards better integration of sustainability in construction project management, but we still face some crucial limitations. The first three limitations will deal with specific steps of the framework. The first limitation relates to step 2 of the framework, namely the selection of relevant work packages and activities, and step 3, namely the selection of a system with associated technologies. Next, we discuss the second limitation, which relates to step 4 of the framework, where the environmental impact scores are calculated. The third limitation questions the fifth step, which involves the distribution of weights given to the relevant work packages or activities. After these three limitations, we will question the framework as a whole. We also discuss three limitations related to this.

First, we currently compare technologies with exactly the same function and scope or at least we assume so. In other words, in step 3 we select systems of technologies that exactly match certain work packages and/or activities (already selected in step 2). In reality, one technology may perform the function of both heating, ventilation and air conditioning, while another technology performs only heating. It is not so evident to equalise the scope between different technologies or systems. Furthermore, a technology or system that performs multiple functions may encompass multiple activities. This creates additional choices in terms of weights for the specific functions/activities.

Second, we discuss the limitations regarding step 4, namely the calculation of the environmental impact score. We highlight two important aspects here. First, we want to address the lack of data. It can be difficult to collect comprehensive data on the environmental impacts of a technology or system, especially for newer or less researched technologies. Second, different datasets (or even methods) of the different technologies can also complicate the assessment of environmental impacts. For example, the energy consumption of different HVAC systems may be measured differently, making it difficult to compare them directly. To calculate the environmental impact score, we conducted a life cycle analysis. For more limitations implied by LCA studies in the construction sector, we refer to Section 3.2, where we already discussed the critiques in the construction sector.

Third, we discuss the limitations of the fifth step, which is the distribution of weights for the relevant work packages and activities. We already noticed that it was difficult to determine the contribution of the work package or activity against the overall environmental impact score of the technology or system. Since we suspect a large impact if the weights are chosen incorrectly, we perform a sensitivity analysis in Section 5.2.4, examining some scenarios where the weights for the work packages and activities are different. Next, in Section 5.2.5, we will carry out a validity check and apply the framework to a second case study. We will also test the effect of different weights on the results for this project. The following three limitations are derived by questioning the entire framework.

Fourth, this framework only considers the environmental dimension of sustainability and not economic, social or other aspects. However, if a sustainability assessment tool could provide an overall score per technology or system that takes into account all dimensions of sustainability, the framework could be easily adapted.

Fifth, analysing each technology separately is very time- and cost-intensive. Each technology requires separate data collection and analysis. This can delay the completion of the construction project and add extra costs to the overall construction budget. An additional difficulty is integrating the individual analyses into a coherent whole, requiring additional efforts to reconcile the data.

A **sixth** major limitation is that interactions of technologies and activities are not included. Analysing technologies separately can lead to a narrow focus on the individual environmental impact of each technology, without taking into account the interrelationship of different systems and components. Imagine the case of analysing the environmental impact of a heating system separately from other building systems. Interdependencies between different systems that can influence the energy efficiency and environmental impact of the heating system are ignored (Eleftheriadis & Hamdy, 2017; Emmerich et al., 2005). For example, the energy efficiency of a heating system is influenced by factors such as the insulation of the building envelope and the airtightness of the building. If the building envelope is not well insulated, more heat is lost through the walls, floors and roof and therefore the heating system has to consume more energy to maintain the desired temperature. If the building is not completely airtight, warm air can escape through cracks, causing the heating system to consume more energy. Moreover, collaboration with other systems, such as the ventilation system, can also have an impact. In case the ventilation system does not distribute warm air evenly throughout the building, some rooms may be colder than others, requiring the heating system to work harder in some rooms. Simply adding up e-scores of the different technologies used in the project leads to an incomplete analysis of the overall environmental impact of the building and therefore opportunities to optimise sustainability performance are missed.

While analysing life cycle impacts by technology can provide valuable information, it is not always the most effective approach to optimising a building's environmental performance. It is important to consider the life cycle of the building as a whole and identify opportunities to reduce environmental impacts holistically. The integration of Building Information Modelling (BIM) and LCA can be an essential step towards achieving building sustainability on a larger scale. In this regard, we refer to some recent interesting papers (Álvarez Antón & Díaz, 2014; Carvalho et al., 2020; Potrč Obrecht et al., 2020; Safari & AzariJafari, 2021; Tam et al., 2022) that elaborate on this.

As we discussed in the third limitation, we suspect that the results are highly sensitive to the weights given to the work packages or activities relative to the overall environmental impact score of the technology or system. Therefore, in the next section, we will perform a sensitivity analysis and focusing on this aspect. Afterwards, we will apply the framework to a second case study to discover the extent to which our results can be generalised. This case study deals with the finishing works of a residential building. The nature of this project is different due to a remarkably smaller duration and cost compared to the industrial complex project. However, we remain in the construction sector.

5.2.4 Sensitivity analysis

In order to test the robustness of our results, we conduct a sensitivity analysis. This considers the impact if the work packages or activities have different weights with respect to the overall environmental impact score of the technology. Specifically, we will adjust the weights for the different heating activities in the industrial complex under investigation. We examine six scenarios, each with different relative contribution of activities to the environmental impact of the technology. The weights per scenario for the different HVAC activities in the industrial complex project are shown in Table 5.5.

			Relative weights per scenario					
ID	**WP / A**	**Name activity**	**1) Base scenario**	**2) Every HVAC activity has equal contribution or weight**	**3) Weights based on baseline costs per activity**	**4) Weights based on duration per activity**	**5) Huge contribution from one specific activity**	**6) Approximately opposite of base scenario**
35	A	HVAC Production hall	30.00%	14.29%	27.84%	27.84%	1.00%	3.33%
56	A	HVAC Storage space	30.00%	14.29%	15.98%	15.98%	1.00%	3.33%
75	A	HVAC Blast cabin	30.00%	14.29%	25.26%	25.26%	94.00%	3.33%
143	A	Pipes in floors and walls 1st (HVAC)	1.67%	14.29%	5.15%	5.15%	1.00%	22.50%
144	A	Pipes in floors and walls on the ground floor (HVAC)	1.67%	14.29%	5.15%	5.15%	1.00%	22.50%
145	A	Pipes in ceilings 1st (HVAC)	2.50%	14.29%	7.73%	7.73%	1.00%	22.50%
146	A	Pipes in ceilings on the ground floor (HVAC)	4.17%	14.29%	12.89%	12.89%	1.00%	22.50%

Table 5.5: Different scenarios for relative weights of the environmental impact score for different HVAC activities for industrial complex

In what follows, we will explain the reasoning behind the scenarios. The first scenario is our base case that we have already examined in Section 5.2.1. Consequently, we will compare this against five other scenarios whose reasoning we will first explain. In the second scenario, we assume that each activity has a similar contribution to the total project. Regardless of duration, cost or other factors, each HVAC activity has the same relative weight. Third, we distribute the weights based on the upfront expected (baseline) cost per activity relative to the total cost of all HVAC activities. The same reasoning is applied in scenario 4, but in this case based on the advance expected duration per activity compared to the total baseline duration of all HVAC activities. The last two scenarios are slightly more extreme. In scenario 5, we start from the assumption that one activity has a huge contribution, while all other activities have a minimal contribution compared to the environmental impact of the total project. Scenario 6 has roughly opposite weights compared to the base case. In the base case, we assume that pipe laying has a small contribution compared to the HVAC activities per room. In scenario 6, it is reversed and the four activities concerning pipe laying have a total contribution of 90%. Based on Table 5.5, we can already conclude that scenarios 3 and 4 will yield identical results. The reason is that there were no fixed costs incorporated in the data for this project. Hence, we only consider hourly costs.

In order to set up the graphs as a function of time and cost, we decided to consider only the ground source heat pump. Including the other technologies would not add value since we are examining the normalised e-scores. Consequently, we only consider the contributions per HVAC activity relative to the sum of all HVAC activities. Through this normalisation, the different technologies would produce the same results per scenario. Our focus here is on evolution and not on the final e-score. Moreover, we only present a linear evolution of cumulative normalised e-scores as a function of time.

We multiplied the weights in Table 5.5 by the total environmental score of 5.97 μPt of the ground source heat pump. We arrived at this value in Chapter 4. We then raised the environmental scores per activity to the -1st power to move from a minimisation to a maximisation problem. Then we normalised the e-scores per technology and in addition, we also normalised the costs. We also performed this procedure in the Plan section to obtain graphs 5.8 and 5.9.

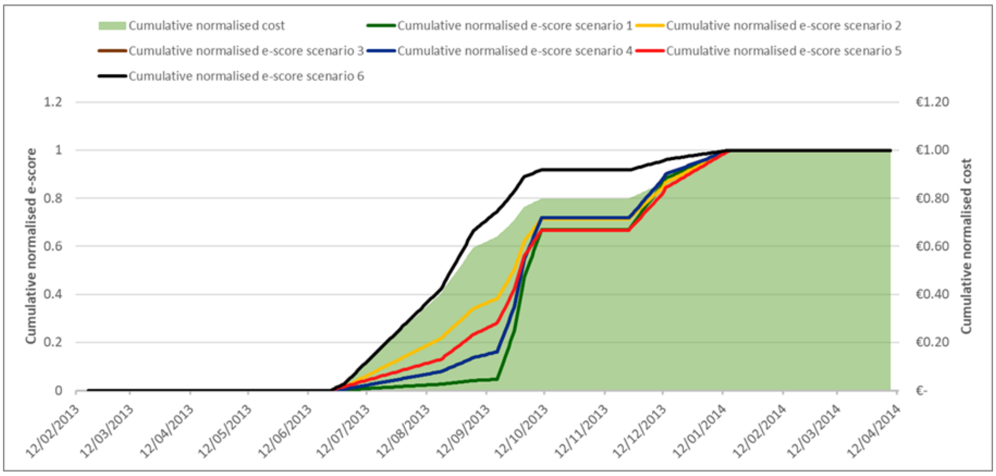


Figure 5.14: Linear evolution of cumulative e-scores and costs for ground source heat pump with different scenarios for weights per HVAC activity

Figure 5.14 depicts the cumulative normalised cost along with the cumulative normalised e-scores for the six scenarios under investigation. From this graph, we can conclude the weights can certainly have a major impact on certain decisions. While in the base scenario we noticed that we could divide the graph into three parts, each with different dynamics of e-score versus cost, this is not necessarily the case for the other scenarios. In the baseline scenario, the first section from 24 June 2013 shows large investments but little contribution from the e-score. Especially in this first section, we observe significant differences between the different scenarios. Especially during that period, scenario 1 comes out worst. Since the final e-scores are identical in all scenarios, the differences between them become smaller. Furthermore, scenarios 2 and 3 have exactly the same evolution of the cumulative normalised e-score, as already seen in Table 5.5. Moreover, we also observe that scenario 6 is extremely different from the other scenarios. While the other scenarios usually have lower e-scores than the investments throughout the project, this is totally not the case for scenario 6. The weights of scenario 6 are furthest away from the baseline scenario, which can also be clearly observed in the graph. Consequently, we can conclude that the weights of the different activities can have a major impact on the results. We will see if this is also the case in the next section, where we apply the framework to a second case study.

5.2.5 Validity

In the previous subsection 5.2.4, we noticed that the extent to which the activities contribute to the environmental impact score has a fairly strong influence on the results and the associated conclusions. To validate, we also extend our research to another project. We still remain in the construction sector but will now examine a residential building instead of an industrial complex. Similar to the previous project, this one is also taken from the DSLIB dataset from the OR&S project data webpage (OR&S, 2015). The project we examine is called "Residential House Finishing Works (1)" and can be found under the ID 107 and the code C2016-16.

The duration of the entire project was initially estimated at 90 working days. Specifically, they were expected to start on 11 March 2016 and were hoping to deliver the project to the client on 14 July 2016. In terms of cost, 54 577.76 € has been budgeted for the finishing works of this residential building. The project was divided into four phases, each representing a work package. The activities we will examine in this section are the plumbing and central heating activities that recur in every phase of this project. Other activities include ventilation, electricity, water connection, roof insulation, plastering, floor insulation, interior carpentry and so on. Some activities recur several times while others only occur in one phase.

Compared to the project concerning the industrial complex, this project is much more limited in scope. While we are now discussing a project of a few months, the previous project involved more than a year and the expected cost was more than 100 times larger. The differences between the two make it even more interesting to explore this project. To avoid repeating ourselves, we are going to move faster on the method. We will dwell on the main conclusions. For this project, we scrutinise only the planning phase and leave out the actual data known after project implementation. We chose this because the actual data of e-scores will not be available after the project anyway.

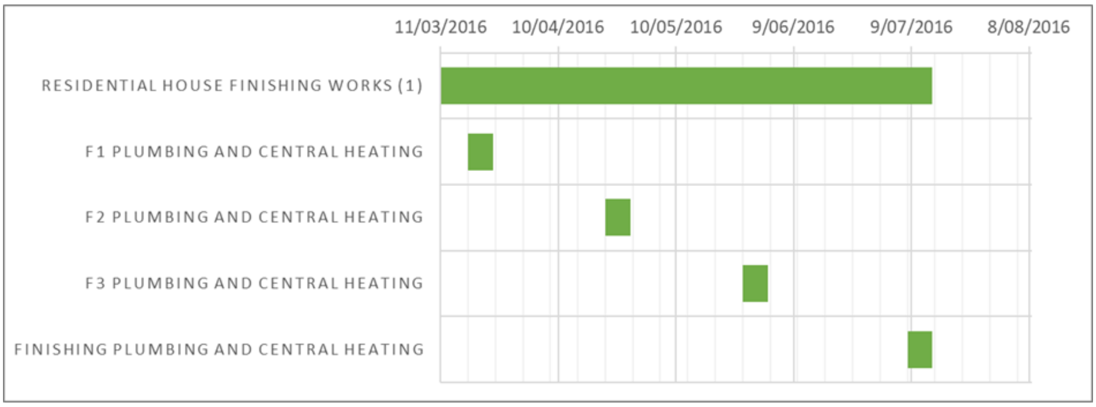


Figure 5.15: Baseline schedule of HVAC activities for residential building project

Figure 5.15 shows the baseline schedule for the project concerning the finishing works of a residential building. The plumbing and central heating activities under consideration are shown along with the planning for the entire project. We note that all four activities are expected to take 5 working days.

For this project, there is no data available regarding the variable cost per hour. However, a fixed cost was budgeted for each activity. The expected costs for these four plumbing and central heating activities are 1288.55 €, 1932.83 €, 3221.38 €

and 6442.75 € per phase respectively. This means that higher costs are expected for these four activities as the project progresses. In other words, the later the activity in the project, the more the expected cost. In terms of both time and cost, these four plumbing and central heating activities together are expected to contribute 20% to the overall project.

Our analysis is structured as follows. First, we start with an evolution of e-scores as a function of time. Similar to the previous project for single technologies, we consider the linear scenario and the scenario where the e-score is earned at the end of the activity. Next, we will normalise the e-scores as well as the costs to plot both as a function of time. In this regard, we will only consider the ground source heat pump, but will elaborate on different scenarios based on relative weights per activity.

Scenarios time - linear and time - end result

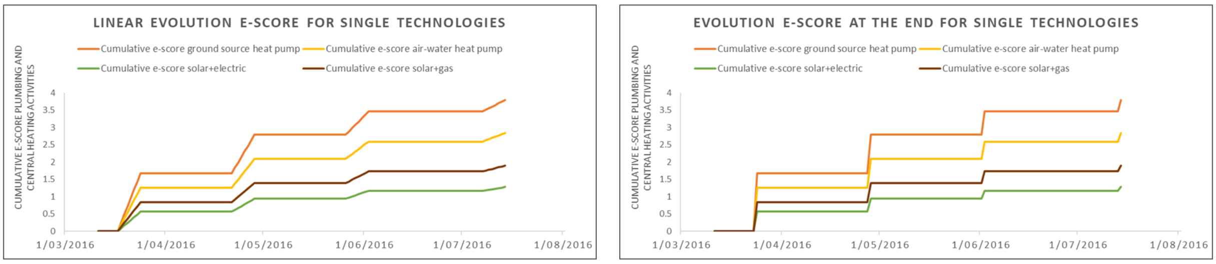
To plot the graphs regarding the evolution of the e-score as a function of time, we need to assign weights to the four plumbing and central heating activities relative to their contribution to the overall impact score of the technology providing heating. Unfortunately, no additional information has been given on what the plumbing and central heating activity per phase entails. On the one hand, this activity takes 5 working days in each phase, but on the other hand, the cost for this activity does increase per phase.

An increase in costs may lead to a worse e-score due to the need for more materials, for example. This is why we currently base the weights per activity on the baseline cost per activity. As a result, we assume that plumbing and central heating activities have a greater contribution to the overall impact score in a later phase compared to the earlier ones. The weights for each relevant activity are shown in Table 5.6. In the next subsection, we will adjust these weights. As in the previous analyses, we multiply the weights by the total impact score of the technology. Afterwards, we raise this value to the -1st power. Consequently, we obtain the results in Table 5.6.

					Absolute weights			
ID	**Name activity**	**Accompanying work package**	**Baseline total cost**	**Relative weights**	**Ground source heat pump**	**Air-water heat pump**	**Solar+electric**	**Solar+gas**
2	F1 plumbing and central heating	Start of execution finishing	1 288.55 €	10%	1.675	1.255	0.565	0.837
25	F2 plumbing and central heating	Phase 2	1 932.83 €	15%	1.117	0.836	0.377	0.558
14	F3 plumbing and central heating	Phase 3	3 221.38 €	25%	0.670	0.502	0.226	0.335
21	Finishing plumbing and central heating	Final finishing	6 442.75 €	50%	0.335	0.251	0.113	0.167

Table 5.6: Absolute weights of the environmental impact score of single technologies for different plumbing and central heating activities for residential building

Figures 5.16a and 5.16b show the progression of the e-score for four possible technologies. Due to the relatively short duration of the plumbing and central heating activities relative to the total project duration, the scenario where the e-score is earned at the end of the activity is not significantly different from the linear scenario. On both graph 5.16a and 5.16b, the ground source heat pump consistently scores best compared to the other technologies. This conclusion is in line with the previous project of the industrial complex.



(a) Scenario time - linear

(b) Scenario time - end result

Figure 5.16: Evolution of cumulative e-scores for scenarios time - linear and time - end result for all four technologies

Scenario time & cost - linear

Also for this case study, we are interested in the results if we include costs. The method for doing so is fully consistent with the one we applied in the case study concerning the industrial complex. We will also consider only the ground source heat pump and normalise both the costs and e-scores. In addition to the weights in Table 5.6 for the plumbing and central heating activities, we propose three other scenarios with different weights for these activities.

Due to the little available information on the residential house project, it is difficult to come up with meaningful scenarios. The weights of the baseline scenario, as explained in the previous subsection, correspond to the contribution of the cost of the activity to the total cost of plumbing and heating activities. Second, we adopt a scenario where each activity has the same contribution to the overall environment impact score. If we distribute weights based on the duration time of the activities compared to the total duration time of all four plumbing and central heating activities, we would get the same weights. The third and fourth scenarios are both extreme, with one activity having remarkably the largest contribution to the total environmental impact score. In the third scenario, this is the first activity as opposed to the fourth scenario where the last activity has the largest environmental contribution. The relative weights are listed in Table 5.7.

			Relative weights per scenario			
ID	WP / A	Name	1) Base scenario	2) Every activity has equal contribution or weight	3) Huge contribution from first activity	4) Huge contribution from last activity
2	A	F1 plumbing and central heating	10.00%	25.00%	85.00%	5.00%
25	A	F2 plumbing and central heating	15.00%	25.00%	5.00%	5.00%
14	A	F3 plumbing and central heating	25.00%	25.00%	5.00%	5.00%
21	A	Finishing plumbing and central heating	50.00%	25.00%	5.00%	85.00%

Table 5.7: Absolute weights of the environmental impact score of single technologies for different plumbing and central heating activities for residential building

For the plumbing and central heating of this project, only the fixed costs are given. For each activity, we have divided these fixed costs evenly over the number of calendar days of the activity. After normalising the e-scores as well as the costs, it is possible to display both visually. Figure 5.17 shows the cumulative normalised e-scores and costs as a function of time for the four scenarios, each with different weights for plumbing and central heating. Although the final environmental impact is the same for plumbing and central heating, major differences can be observed during its evolution. Especially the difference between the two extreme scenarios is very large. Moreover, the duration of this project is relatively limited. In other words, for a relatively short period, there can still be significant differences.

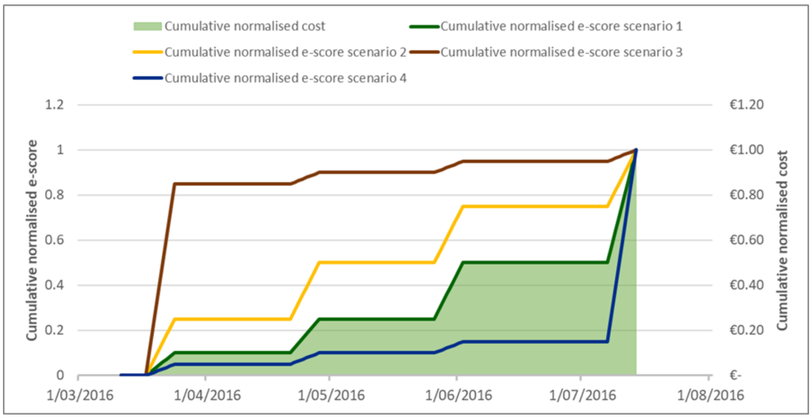
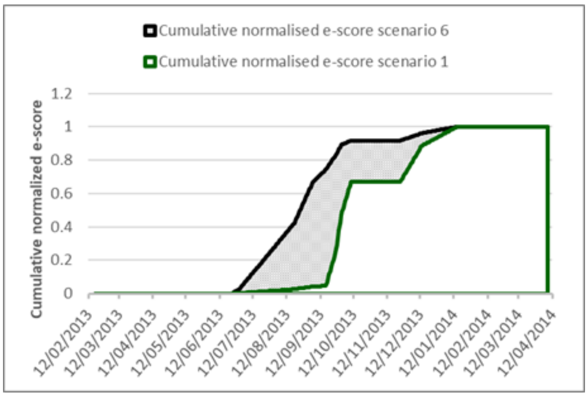
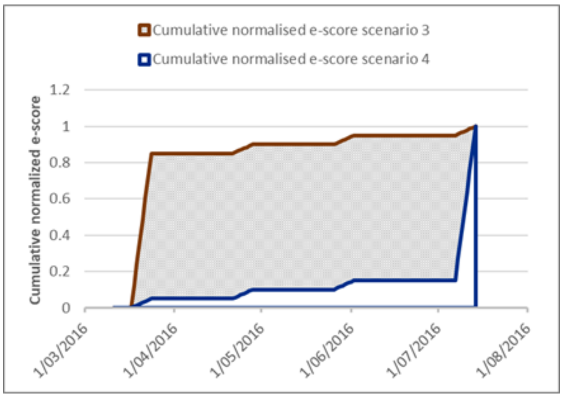


Figure 5.17: Linear evolution of cumulative e-scores and costs for ground source heat pump with different scenarios for weights per plumbing and central heating activity

This contrasts with the industrial complex project, where the differences were less pronounced but extended over a longer time period. To compare the cumulative normalised e-scores of the two projects, we present them in Figures 5.18a and 5.18b. These figures take the most diverse scenarios from Figures 5.14 (for the industrial complex project) and 5.17 (for the residential house project) and do not show the cumulative normalised costs for clarity. We can conclude that the graphs showing the cumulative normalised e-scores clearly indicate different dynamics for the two different case studies. For project managers, both scenarios are possible.



(a) Two extreme scenarios for weights of activities in project "Industrial Complex"



(b) Two extreme scenarios for weights of activities in project "Residential House Finishing Works"

Figure 5.18: Linear evolution of cumulative normalised e-scores for ground source heat pump for two different projects

The grey area marked on both graphs (5.18a and 5.18b) is determined by two aspects. On the one hand, it depends on the time period. This refers to the duration of the project or more specifically of the relevant activities. On the other hand, it is also important how e-scores are modelled. This depends on the expected scenario for the evolution of e-scores and when the relevant work packages and activities are located.

These two figures and grey areas clearly illustrate that project managers can face different situations. In the industrial complex project, the differences seem much smaller, which is why we would assume it has little impact which technology you choose. However, this project is remarkably longer and more expensive than the finishing works of residential house project. For this second case study, the dimensions of the grey area are completely different as time is relatively limited, but the difference in this small time span is very large. Based on this second case study, we can conclude that activity weights can play a major role.

5.3 Conclusion

We conclude our analysis by briefly reviewing our main findings. Based on the graphs showing the evolution of the e-score as a function of time, we found that large discrepancies were possible between different scenarios. The reasons for this can be attributed to critical decisions that were also specified in the framework. The first three steps are selection steps that serve as the basis for subsequent calculations. In addition, the calculation of the environmental impact scores for the different technologies or systems under consideration is also of crucial importance. This score determines the final environmental impact of the project, regardless of how it evolves during the project. As a result, this is a critical parameter in the decision-making process for project managers/teams. Throughout this chapter we have explored different options for the last two steps of the framework, namely distributing the weights of the activities and displaying the e-scores as a function of time.

In our analysis we showed that the distribution of weights among the activities with respect to the overall environmental impact score of the associated technology had a major influence. While in some scenarios with different activity weights the e-score was fairly evenly earned, other scenarios were more extreme with the majority of the e-score earned at the beginning or end of the project. The choice of weight distribution between the different relevant activities had a significant impact on the increment of the e-score per time unit. As a result, project managers could be faced with highly diverse scenarios that could influence their final decision on a particular technology.

In addition, the last step of the framework also proved to be influential as it determined the evolution of the e-score and considered the e-score relative to time and/or cost. During a linear evolution of the e-score, the e-score increased gradually while for the scenarios concerning cascading and certainly concerning end result, the progression was more radical. Consequently, the period over which the e-score was earned was clearly affected by the differences in the evolution of the e-score. We can conclude that the framework provides a clear overview of crucial decisions to be taken in order to integrate the environmental impact of green technologies into (construction) project management practices.

Discussion

With this thesis, we hope to contribute to the integration of sustainability into construction project management. Throughout our literature review and analysis, we identified some gaps and limitations that provide opportunities for further research and action. We find that integrating sustainability into project management is still rarely put into practice. Using a life cycle analysis, we calculated an environmental impact score for each technology to support project managers/teams in their decision making. In our view, there is certainly potential for further exploration, and this has been confirmed by practitioners using LCA-based tools in their project management practice. However, LCA provides only a general framework and not an exact technique for calculating environmental impacts. Moreover, it only considers the environmental dimension of sustainability which means that there is a need for a global sustainability assessment tool that covers all dimensions of sustainability.

We start by discussing the integration of **sustainability into project management in practice**. Despite the fact that a growing number of companies have identified sustainability as a strategic priority, several several global surveys by McKinsey (2023) show that the majority of multinational companies have yet to operationalise sustainability (Sroufe, 2017). Consequently, there is clearly a gap between perception of importance and actual implementation of sustainability in practice. The results of the study by Martens & Carvalho (2016) show that this gap also applies to the integration of sustainability in project management processes. Fortunately, we refer to a number of papers (El-Haram et al., 2007; Økland, 2015; Robichaud & Anantatmula, 2011; Stanitsas et al., 2021; Tharp, 2013; Toljaga-Nikolić et al., 2020) that respond to this research gap. In order to address this gap, there is a need to develop tools, techniques and methodologies that assess sustainability and can be applied in project management practice.

In our analysis, we applied the **life cycle analysis** methodology for different technologies used in construction projects. The choice of LCA implies that we have only considered the environmental impact of the technologies, and consequently excluded other dimensions of sustainability. In addition, when applying LCA to construction projects, we have abstracted the underlying endpoint and midpoint factors. Moreover, we had to make several choices and assumptions in our analysis, such as the scope and a particular impact assessment method. We also did not collect primary data in the field, but merely used secondary data via databases. To verify the implications of these choices, we should ideally carry out a life cycle analysis based on real-world data with varying scopes, impact assessment methods, etc. Conducting this correctly would be very time-consuming and requires extensive knowledge of the technologies themselves. This can be an obstacle for companies to apply LCA to construction project management.

For this issue, we consulted Charlotte Dossche who has conducted LCA studies as a researcher at the University of Ghent. She currently applies this knowledge in practice at Bopro (Bopro, 2023), which focuses on responsible, sustainable developments and real estate projects across Europe. Bopro embraces the fact that how we will design, build and operate the space and its buildings will play an important role on the path towards the European goal of becoming a climate neutral continent by 2050 (Bopro, 2020). Bopro is realising the potential of **life cycle analyses in practice**. In the past it was used more as a reporting tool in the context of BREEAM projects, but nowadays LCA (Dossche, 2023; Bopro, 2020) has evolved into a decision support tool where external environmental costs are reported in addition to characteristic values (e.g. kg $CO2$ eq.). Monetising environmental indicators (Krieg et al., 2013; Durão et al., 2019; Arendt et al., 2020) reflects the damage to the environment that is not included in the investment price of a product, but is passed on to society. It is valuable to know how a company like Bopro implements LCA in its daily practice. Similar to our objective in this thesis to compare different alternative technologies, this is also an objective pursued by Bopro. In addition, it also prefers to incorporate building-level assessments and comparisons into its decisions. For both objectives, Bopro (Dossche, 2023; Bopro, 2020) primarily employs the global software program **One Click LCA** (One Click LCA Ltd, 2023b) and **TOTEM** (TOTEM, 2023), a tool specialised on the Belgian context jointly released by the three regions in Belgium. With real-life data from construction projects, these tools are more accessible than the SimaPro software we used in Chapter 4. Since we have not collected primary data from construction projects, we will not apply these tools ourselves. In our opinion, however, this would be valuable for future research.

While LCA offers the potential to assess the environmental impact of buildings or construction projects, the other dimensions of sustainability should not be neglected. To compare the sustainability of buildings, projects or different options within a project, there is a **need for a unified global sustainability assessment tool**. According to Mahmoud et al. (2019), the various attempts to develop this global assessment tool have not yet been successfully established because uniform attributes for sustainability assessment have still not been agreed and recognised. Moreover, the majority of sustainability assessment tools Mahmoud et al. (2019) prove ineffective when applied internationally due to the lack of effective weighting in their assessment models. The research by Mahmoud et al. (2019) may already be a promising step in the right direction towards a global sustainability assessment tool that can support project managers/teams in their project management practices and their decision making.

Conclusion

In this thesis, we investigated the integration of sustainability in construction project management. This is critical to addressing the challenges facing the construction industry. In order to provide project managers and teams with guidance on how to include the environmental impact of green technologies into project decisions, we have developed a framework in this thesis. This framework consists of six steps of which the first three are selection steps. After selecting a construction project, the relevant work packages and activities are selected and a system consisting of one or more technologies is created. The fourth step is of major importance and involves calculating the environmental impact score of the chosen system. In this thesis, we relied on life cycle analysis for this purpose. In the fifth step, we determined weights for the selected work packages and activities according to their contribution to the overall environmental impact score of the associated system. Finally, we moved from environmental impact scores to e-scores which are important quantitative metrics for project managers. For the e-scores, we discussed some scenarios depending on their progression during the project. Based on this framework, we hope to provide a starting point on which to build to ensure that environmental impacts are (more) integrated into construction projects.

By calculating the environmental impact scores of technologies that produce heat, we gathered some interesting insights. We have calculated the environmental impact scores using a life cycle analysis for individual technologies and combinations of technologies. For the examined individual technologies aimed at heat generation, the range of environmental impact scores is between rounded 6 µPt and 18 µPt. For the combinations of heat generation technologies, the range of environmental impact scores is between rounded 18 µPt and 26 µPt. Furthermore, we found that heat pumps scored significantly better from an environmental point of view compared to the investigated solar systems. The ground source heat pump emerged as the most environmentally friendly with the least environmental impact, shortly followed by the air-water heat pump. Using the IMPACT 2002+ impact assessment method, four midpoint impact categories emerged that consistently showed relatively high values. Mainly 'non-renewable energy' was significant, but also 'global warming', 'respiratory inorganics' and 'terrestrial ecotoxicity'. We incorporated these insights when we applied the framework to the industrial complex project and the residential house project. This showed that project managers could face different challenges depending on the evolution of the e-score and the project.

Based on this thesis, we would like to highlight three more aspects that are relevant to include for future research. Integrating environmental impact into construction management is already very important, but to respond to sustainability, other aspects must also be considered, such as economic and social. This requires the use of other sustainability assessment tools, possibly in conjunction with LCA. Since current assessment tools are often criticised for taking a narrow view of sustainability and do not cover all aspects, this is a difficult but interesting and worthwhile challenge. Secondly, it is difficult in practice to collect and use the data needed to calculate an environmental impact score. Both data availability and quality are crucial for drawing valuable conclusions. An internationally comparable data inventory could make an significant contribution. Finally, we also recommend performing the sustainability assessment on an entire project and not necessarily limiting it to (green) technologies or systems of technologies, resources, etc. In addition to green technologies, other influencing factors such as building envelope insulation, architectural design, building orientation and energy efficiency should also be considered. In general, our analysis is subject to numerous assumptions that can be questioned in future research. Hopefully this thesis can serve as a starting point to build on.

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