UHASSELT
KNOWLEDGE IN ACTION

Faculteit Bedrijfseconomische Wetenschappen

master handelsingenieur in de beleidsinformatica

Masterthesis

Impact of the energy price shock on data centers in Belgium

Tuur Anthonissen

Scriptie ingediend tot het behalen van de graad van master handelsingenieur in de beleidsinformatica

PROMOTOR :
Prof. dr. Robert MALINA

BEGELEIDER :
De heer Tuan NGUYEN

2022
2023

UHASSELT
KNOWLEDGE IN ACTION

www.uhasselt.be
Universiteit Hasselt
Campus Hasselt:
Martelarenlaan 42 | 3500 Hasselt
Campus Diepenbeek:
Agoralaan Gebouw D | 3590 Diepenbeek

Faculteit Bedrijfseconomische Wetenschappen

master handelsingenieur in de beleidsinformatica

Masterthesis

Impact of the energy price shock on data centers in Belgium

Tuur Anthonissen

Scriptie ingediend tot het behalen van de graad van master handelsingenieur in de beleidsinformatica

PROMOTOR :

Prof. dr. Robert MALINA

BEGELEIDER :

De heer Tuan NGUYEN

Samenvatting

Onzekerheden op en rond de energiemarkt hebben geleid tot aanzienlijk hogere energieprijzen dan voorheen. Deze stijgende energieprijzen veroorzaken kopzorgen bij energie-intensieve bedrijven die sterk afhankelijk zijn van een betrouwbare en betaalbare energievoorziening. Binnen de ICT sector neemt de afhankelijkheid van energie een prominente plaats in. Datacenters, die een essentieel onderdeel zijn van deze sector, verbruiken jaarlijks 1,0 – 1,4% van de wereldwijde elektriciteit. Voor de opkomst van de stijgende energieprijzen vormden de energiekosten van een datacenter al een aanzienlijk deel van de totale operationele kosten. Echter, met de recente prijsstijgingen wordt de impact van deze kosten nog groter en vormt het een uitdaging voor bedrijven die sterk afhankelijk zijn van deze energie-intensieve infrastructuur. Het vinden van oplossingen om de energiekosten te beheersen en te verminderen wordt steeds urgenter in deze context van onzekere en stijgende energieprijzen. Vandaar volgende onderzoeksvragen:

1. Hoe heeft de schok in de energieprijzen invloed op datacenters?
2. Wat zijn de strategieën voor datacenters om de schok op te vangen?

De methodologie die is gebruikt om antwoorden te geven op de volgende vragen is als volgt uitgevoerd. Eerst is de stijging in energiekosten geanalyseerd vanaf enkele jaren voor het begin van de prijsshock. Het effect op de energiekosten wordt gegeven over de periode van 2018-2027. Vervolgens wordt ook het verschil bekeken tussen datacenters met een betere strategie omtrent energie efficiëntie. Daarnaast is een kosten-baten analyse uitgevoerd voor verschillende hernieuwbare energieprojecten om de voor- of nadelen van deze strategieën te achterhalen. Tot slot wordt het potentiële competitief voordeel geanalyseerd van een datacenter met een optimaal energiebeheer t.o.v. een datacenter met een slecht energiebeheer.

Uit deze methodologie zijn de volgende inzichten verkregen. De jaarlijkse energiekosten van een datacenter zijn op de piek van de prijsshock mogelijks gestegen met 670,84%. Voor de prijsshock hadden de energiekosten van een datacenter met een jaarlijks verbruik van 12,5 GW de grens van € 750 000 niet overschreden. Sinds de prijsshock in 2022 is de energiekost boven € 1 000 000 en wordt niet verwacht dat dit voor 2027 zal dalen tot het niveau als voorheen.

Vervolgens zorgen maatregelen omtrent energie efficiëntie voor significante voordelen in de jaarlijkse energiekosten, zowel tijdens de prijsshock als bij lagere energieprijzen. Verbeteringen in het beheer van de IT-apparatuur, de koelingssystemen en de systemen voor stroomvoorziening kunnen zorgen voor een verlaagd energieverbruik en uiteindelijk voor een verlaagde energiefactuur.

Bij de analyses omtrent de hernieuwbare energie projecten is bevonden dat een investering over het algemeen een voordeel met zich meebrengt. In de kosten-baten analyse zijn vier projecten geanalyseerd. De vier projecten zijn onderverdeeld in drie projecten met zonne-energie en één project met windenergie. De drie zonne-energie projecten hebben een potentiële energieproductie van 103 542 kWh/jaar, 997 870 kWh/jaar en 2 494 674 kWh/jaar. Voor het windenergie project wordt een potentiële productie van 3 600 000 kWh/jaar gerekend. De netto contante waarden zijn positief bij alle projecten in verschillende prijsscenario's. De *Levelized Cost of Electricity* (LCOE) geeft aan wat de kost per kWh kan zijn voor de verschillende projecten en geeft een vergelijkingsbasis tussen

de projecten. Hieruit blijkt dat het kleinste zonne-energie project en het windenergie project een hogere LCOE hebben dan de andere projecten. In de scenario's waarin de prijsshock is meegerekend zullen deze projecten, zoals eerder aangegeven, financiële voordelen met zich meebrengen. Echter zijn er wel duidelijke verschillen op te merken in het scenario van een investering in het jaar 2023. Uit verdere analyses van dit scenario blijkt dat er aanzienlijke verschillen zijn in de niveaus waarop de netto contante waarden break-even zouden zijn. Bij een verminderde energie productie zullen het kleinste zonne-energie project en het windenergie project al een financieel nadeel met zich meebrengen bij een afwijking van minder dan 10% in de energie productie. Terwijl dit bij de andere twee projecten veel hoger ligt.
Tot slot zouden investeringen in energie efficienctie en een effectief hernieuwbaar energieproject een significant competitief voordeel met zich meebrengen, ook in tijden waar de energieprijs licht stabiliseert. Indien data centers ervoor kiezen om zich dit jaar nog intensief in te zetten op deze zaken, zal dit stelselmatig een significant competitief voordeel met zich meebrengen.

Zowel de minister als een studie geven aan dat tot op heden Belgische data centers niet voldoende inspanningen leveren om hun energieverbruik te verminderen en in te zetten op duurzaamheid. Ook hadden uitbaters van data centers kopzorgen omtrent de grote van de impact van een aanhoudende verhoogde energie prijs op de lange termijn. Momenteel is het voor datacenters mogelijk om op korte termijn de extra kosten door te rekenen aan de klant. Echter is dit op de lange termijn geen strategie die men kan volhouden. Deze studie geeft een beeld over de stijgende energiekosten voor datacenters en probeert, met behulp van een versimpelde financiële weergave, enkele mogelijkheden duidelijk te maken. Ten eerste zullen investeringen in energie efficiëntie voordelen met zich meebrengen en het gewicht van de energiekosten verlichten, ongeacht de toekomstige energieprijs. Belangrijk om hierbij te vermelden is dat de investeringen gericht en onderbouwd uitgevoerd moeten worden. Hiermee wordt bedoeld dat een energie audit vooraf moet gaan aan de investeringen zodat de verbetering effectief zullen zijn. Ten tweede kunnen on-site hernieuwbare energieprojecten de afhankelijkheid van de datacenters op de energiemarkt verminderen en tegelijkertijd een financieel voordeel creëren. Echter geven de resultaten aan dat bij deze investering een duidelijk plan gemaakt moet worden dat onderbouwt is met een diepgaande studie, aangezien niet elk project even voordelig zal zijn. Tot slot wordt duidelijk gemaakt dat het mogelijk is om op basis van goed energiebeheer een competitief voordeel op te bouwen.

Op basis van literatuur en internetgegevens zijn aannames gemaakt, waardoor het niet mogelijk was om diepgaandere analyses uit te voeren. Aspecten zoals het energieverbruik van elk type apparaat en variaties in energiekosten gedurende bepaalde periodes van het jaar zijn niet onderzocht. Daarnaast geven de gepresenteerde cijfers mogelijks een overschatting van de werkelijkheid weer. Datacenters kunnen, net als andere energie-intensieve bedrijven, hun energiecontracten onderhandelen met de leveranciers. Hierdoor kan de werkelijke energieprijs enorm afwijken van de prijs die gebruikt is in deze studie. Ook wordt bij de uitwerking van de hernieuwbare energieprojecten ervan uitgegaan dat alle geproduceerde energie kan gebruikt worden als vervanging van de aangekochte energie. Verder was het niet mogelijk om de analyses omtrent energie efficiëntie en de hernieuwbare energie uit te breiden door een gebrek aan eenduidige en transparante data.

Assumpties over investeringen in energie efficiëntie en het verdienmodel van een datacenter konden niet gemaakt worden.

Het is belangrijk om op te merken dat deze beperkingen de nauwkeurigheid en generaliseerbaarheid van de resultaten kunnen beïnvloeden. Hierdoor dient deze studie als een aanzet tot intern onderzoek met werkelijke en betrouwbare gegevens.

Acknowledgments

The completion of this master's thesis, and thus the culmination of my studies, would not have been possible without the trust and support of the important individuals around me.

I would like to express my gratitude to my supervisor, Professor Robert Malina, for his valuable feedback, which he provided with great attention and expertise. I also wish to thank my mentor, Tuan Nguyen, for his excellent guidance and encouragement throughout the entire process. Additionally, I would like to extend my thanks to my family and friends for their unwavering support during this final year of my university studies. Lastly, I would like to express my gratitude to UHasselt and to everyone who has shaped me during my academic journey into the person I am today. Studying at UHasselt has provided me with numerous insights.

Table of contents

1 Introduction

The European energy sector has faced significant challenges due to the COVID-19 pandemic and the ongoing Ukraine war, leading to disruptions across various industry segments. The pandemic-induced lockdown measures resulted in a substantial decline in energy demand and financial difficulties for consumers, leading to increased energy prices once the restrictions were lifted [1]. The situation worsened with Russia's invasion of Ukraine, as the EU heavily relies on energy imports. Consequently, the decision to halt the imports of Russian fossil fuels caused energy prices to soar to unprecedented levels, raising concerns about energy security and creating uncertainties within the EU [2].

The need for an energy transition in the EU to meet current and future energy demands has become apparent. However, the prevailing high energy prices and the associated uncertainties in energy security pose significant challenges, particularly for energy-dependent sectors, jeopardizing their progress [3]. One such sector heavily reliant on energy is the Information and Communication Technology (ICT) industry. Data centers, which play a crucial role in the ICT sector, consume a considerable amount of global electricity, accounting for approximately 1.0 - 1.4% [4]. These data centers encompass physical facilities that house IT infrastructure and computer services used by businesses and organizations to store and process data [4].

Within the energy consumption of data centers, two primary categories can be identified: IT equipment (such as servers, networks, and storage) and infrastructure facilities (including cooling and power conditioning systems) [5]. With the projected growth in data center energy consumption driven by the increasing demand for IT services, extensive research is being conducted to explore methods of enhancing energy efficiency. The EU has also introduced a Code of Conduct aimed at guiding and encouraging data centers to reduce their energy consumption [4].

Considering the uncertainties stemming from the energy sector and the growing importance of energy efficient data centers, this thesis aims to investigate the impact of the energy crisis on local data centers. The study of existing academic research on the energy consumption of data centers shows that data centers are growing energy-intensive companies. Energy is important for the daily operation of a data center. Even though data centers heavily invest in equipment and methods to become more energy efficient, energy costs will remain the most significant expenditure in the data center cost structure.

Given the reliance on energy for data centers for their daily operation, this thesis aims to provide insight into the effect of certain parameters on the electricity bill of a data center.

Consequently, the research questions are as follows:

1. How does the energy price shock affect data centers?
2. What are strategies for data centers to cope with the shock?

The insight gained by answering these questions can move data centers towards more sustainable investments to limit their energy consumption and dependence on non-renewable energy. The Belgian minister of telecommunications has asked the Belgian data centers to raise their efforts to become more sustainable [31]. A study by the Belgian Institute for Postal Services and Telecommunications (BIPT) (2022) shows that Belgian data centers are still not very concerned with sustainability [32].

2 Energy use cost and efficiency in data centers

2.1 Energy Costs of a Data Center

The increasing demand for data center services has led to a growing and competitive data center sector. In a competitive sector, the need for efficient management is high [8]. Customers seek cost-effective services without compromising on quality. The competitiveness creates pressure for data center owners to minimize the total cost of ownership while meeting the agreed-upon quality of service per service level agreement [9]. Chen et al. (2016) mentions that the total cost of ownership for a data center consists of two types of cost, capital cost, and recurring operating cost [10].

Due to differences in the management of a data center, a precise distribution of the total cost of ownership is hard to make [11]. In general, research shows that operating costs dominate the total cost of ownership [10]. Operating costs include energy costs, maintenance costs, and salaries [10]. Customers expect that the services of a data center are available at all times, meaning operations that are continuous while meeting the required quality. To run these operations servers, storage equipment, cooling systems, network equipment, power supply systems, and lightning have to be supplied by energy [12]. Resulting in an electricity bill that can amount to 50% of the operating costs [13][14]. A high share of energy costs that can influence the operating costs gives an even greater incentive to work towards efficient management. Data centers can use the Power Usage Effectiveness (PUE) metric to measure their energy efficiency [4]. The PUE gives a ratio of the total annual energy consumed to the annual energy consumed by IT equipment [4][11]. A significant cost advantage can be gained by a slight change in PUE [11]. Expectations about data centers are that the energy demand will have steady growth and may even consume one-fifth of electricity production in 2050 [15].

Important to note is that besides internal management, external factors can also affect the energy cost of data centers. The energy expenses of a data center are dependent on the price paid per kWh. [16] refer to reports of the EU that estimate an annual 5% rise in electricity prices. Another factor that can influence energy costs is policy decisions taken by governments. Regulations on carbon emissions, i.e. taxes, can raise the total energy cost for a data center [17].

Energy consumption of data centers has gained attention from researchers to find energy efficient practices for data centers. Both data centers and the customers can gain advantages from improvements in energy efficiency because lower operating costs can lead to lower prices charged for the services [18].

2.2 Best Practices for Energy Efficient Data Centers

Research carried out by the industry, academics, and policymakers have to lead to several best practices that can support data center owners in reducing the energy consumption of data centers.

The EU constructed a Code of Conduct in 2008 to create awareness around the increasing energy consumption of the data center industry [4]. The Code of Conduct is a voluntary approach in which participants agree to monitor their energy consumption and to implement at least minimal energy efficiency practices. With this Code of Conduct comes a yearly updated list of best practices and guidelines that can be used as a reference document for the data center owners [19]. Reference [19] gives a detailed list of best practices. In this review, a broader overview will be given of the areas in which data centers can increase their energy efficiency.

The energy consumption of a data center can be divided into three categories: IT equipment, cooling, and power supply. The distribution of these categories can differ in each data center. In general, IT equipment accounts for 50% of the total energy consumption in data centers, while cooling and power supply contribute 40% and 10% respectively [20]. Best practices are suggested in these categories, these will be introduced in the following sections.

2.2.1 Energy Efficiency in IT Equipment

When selecting and managing IT equipment, the energy efficiency performance of the devices must also be considered a high-priority decision factor [19]. IT equipment refers to computation, storage, network, and monitoring equipment [21]. The EU launched a policy to improve the energy efficiency of products, this policy is called the Ecodesign Directive. In the Ecodesign Directive minimal requirements, like energy efficiency and recyclability, are set for products to promote the development of environmentally friendly technologies [22]. Recently computing and storage equipment that are used in data centers are added to the Ecodesign directive [23]. This can support data center owners to monitor their current IT equipment and to select new IT equipment if necessary.

Another best practice that can be used to manage IT equipment is virtualization and consolidation. The virtualization and consolidation strategy is designed to tackle the problem of underutilized servers. The industry-wide average of servers in idle mode i.e. turned on without performing computations, is at least 20% [23]. With consolidation, workloads that are normally carried out by multiple under-utilized servers are combined in a smaller number of servers that run on higher capacities [24]. This is enabled by virtualization, a technology in which a physical server can host multiple virtual servers. Reducing the number of servers in idle mode and resulting in a potential energy savings of 10-15%[23].

2.2.2 Energy Efficiency in Cooling

Cooling systems are essential for data centers during operation to prevent equipment breakdowns. The cooling systems must be able to absorb the heat produced by IT equipment [25]. The two main strategies used for cooling systems are air cooling and liquid cooling systems. An air-cooled system produces and distributes chilled air and captures warm air by using a computer room air conditioning unit [21]. A best practice for this strategy is cold and hot aisle containment. In this practice, each piece of hardware in a line faces the same direction, causing hot air to escape on one side and cool air to come out on the other [24]. With properly planned aisle containment, the temperature set points of the cooling equipment can be increased. With an increase of 1°C leading to an electricity saving of approximately 5% [23].

The liquid cooling strategy is a growing strategy replacing the more dominant air cooling strategy. Liquid cooling offers a higher energy efficiency than air cooling and can handle higher heat densities [23]. In this strategy, a cooling liquid is brought up near the heat source, the processor chips, and other devices in the data center. The cooling liquid then replaces the liquid for heat removal that is circulating inside the device [17]. The downside to this strategy is the high capital expenditure that comes with implementing this strategy [24].

A best practice that can improve the energy efficiency of both strategies is free cooling, which utilizes natural cooling resources. An example of this is direct airside free cooling, where outside air is directly brought into the data center [21]. This requires that the data center is situated in an area with a generally cold environment [23]. Although one technique under consideration is to increase the temperature in an IT room, making the use of free cooling possible at higher outside temperatures [21].

2.2.3 Energy Efficiency in Power Supply

The power supply of a data center is controlled by the power distribution system. In this system, the Uninterruptible Power Supply (UPS) is an important part. The main function of the UPS is to deliver a continuous supply of power when the main supply fails. Another possibility is that all the power that is provided by the grid runs through the UPS. Older and less efficient UPS units convert AC power from the grid to DC power and then back again to AC power to supply the data center, high energy losses are possible due to the double conversion. This requires monitoring of the UPS system for data centers still using this type of process [21]. In the Code of Conduct general efficient UPS units and their use, are recommended [19].

2.3 Energy Contracts for Energy-intensive Companies

Data centers are seen as energy-intensive companies. According to an estimation made of the data from Avgerinou et al. (2017), an average data center consumes 13 GWh/year [4]. As previously mentioned, the operating costs of a data center are dominated by energy costs. This means that in most cases data centers become dependent on the energy contract with the energy supplier. A study carried out by CREG (2021), Belgian Federal Commission for Electricity and Gas Regulation, indicates that a Belgian industrial user concludes an energy contract in two ways. First, an energy contract can be concluded against a fixed price. In a contract against a fixed price, the supplier calculates the price offer based on the main futures calendar quotation of the day the offer is submitted. For this type of contract, the moment that the contract is concluded can be of great importance. Second, an energy contract can be concluded against a fixed price based on clicks. Almost nine out of ten industrial users have a contract with a price that is based on clicks [27]. The term clicks are meant that the industrial user can select several preferred market prices at different moments in time. Based on the clicks, in between a predefined time period in the contract, an average price is calculated for the supplying period [27]. Another study by CREG (2022) shows that the contracted energy price has been on the rise since 2017, and this increase has been reinforced in 2021 [28]. According to the study findings, by 2021, approximately 50% of energy supplier customers were paying electricity prices ranging from 60 €/MWh to 90 €/MWh [28].

2.4 On-site Generation of Renewable Energy

Another strategy to lower the electricity bill of a data center, instead of lowering the energy consumption by energy efficiency, is an on-site generation of renewable energy. With on-site generation, the location has immediate access to renewable energy sources [21]. In areas where electricity prices are high, on-site generation can be an affordable and environmentally good alternative [25]. Reliability is an important aspect of data centers, meaning that a stable energy supply is needed to have optimal functionality. When implementing on-site renewable energy sources as the primary source of energy supply several problems arise. First, it will take a large area of PV panels to supply a portion of the energy needed to run the data center [21]. Second, energy sources like PV panels and wind power don’t deliver consistent electricity during the whole day. Third, on-site generation is dependent on the location of the data center and this may not be optimal for solar or wind power [29]. To support the decision for an on-site generation project with solar or wind power, the Saint-Ghislain Google data center is given as an example [30]. With the solar project, the energy demand of the data center from the grid is lowered. Although the total energy supply met is relatively small, it is sufficient to provide annual power to the water treatment plant, which plays a crucial role in cooling the data center [30].

To decide whether to initialize an on-site solar power generation project or an on-site wind power generation project several costs can be considered. The costs provided are taken from the report filed by IRENA, the International Renewable Energy Agency.

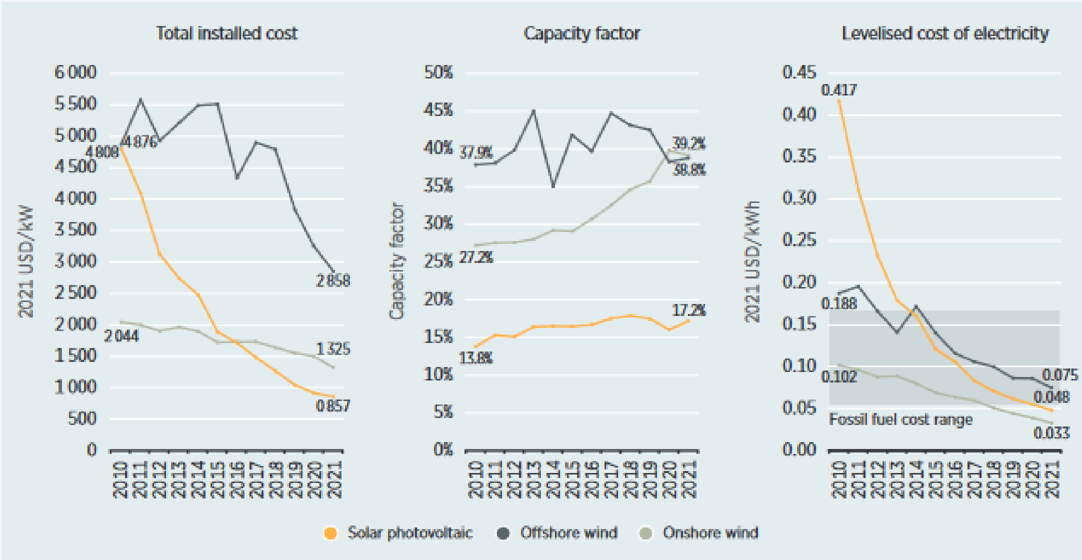

Figure 1 Global weighted average total installed costs, capacity factors, and LCOE of newly commissioned utility-scale solar PV, onshore and offshore wind, 2010-2021 [1]

Figure 1 gives important factors that can be considered by comparing different energy source projects. A solar power project has an advantage in lower installed costs but will run less at maximum capacity. An on-site wind project is more expensive than a solar project but has a capacity factor that doubles the capacity factor of solar power. Lastly, the levelized cost of electricity shows that the net present cost of electricity generation by either on-site wind or solar is cheaper than fossil fuel electricity generation [30].

3 Methodology

3.1 Research Design

As previously mentioned, this research consists of two parts. In the first part, the effect of the price shock on data centers with different energy efficiency strategies is analyzed. Different energy models are set up for a data center. The baseline is a data center with a total yearly energy consumption of 12.5 GW and a Power Usage Effectiveness (PUE) of 1.8. The baseline will be compared to data centers with the same amount of yearly IT energy consumption but with better PUE values, being 1.25 and 1.09. When these energy models are set up, the electricity costs over a ten year period will be calculated. To calculate these costs the electricity prices from 2018-2027 are used. A first comparison is made between the baseline without the price shock scenario and the baseline with the price shock scenario. This will provide an insight into the extra electricity cost that the price shock caused. Next the electricity cost of the baseline is compared to the more energy efficient data centers. This may give a view in the budgetary savings more energy efficient strategies can deliver during the price shock. Lastly, the yearly costs of electricity without the price shock of the three data centers are compared.

In the second part, renewable energy strategies are analyzed that can potentially reduce the share of the electricity costs in the operational costs. These strategies will consist of three projects of photovoltaic systems (PV) and one wind turbine project. A cost-benefit calculation is done to gain insight into the financial gains the projects may have. First, the projects are compared with the Levelized Cost of Electricity. The method of LCOE enables a comparison to be made between power plants that have varying generation and cost structures [37], the lower the LCOE the more desirable the project. The calculation of LCOE involves analyzing the total costs incurred during the power plant's lifetime, including construction and operational expenses, and comparing them against the total amount of energy produced [37]. After the comparison, the costs and benefits of the projects are calculated over their lifetime, starting from the year 2018. The costs of the projects consist of investment costs and operation and maintenance (O&M) costs. The benefits are calculated by subtracting the electricity costs of the data center with renewable energy from the electricity costs without renewable energy. The net present value (NPV) will say if it is advantageous to invest in the renewable energy project or not. As the NPV can be influenced by the electricity price, three scenarios about future electricity prices are used in the calculations.

At last, a comparison is added of the electricity costs of a data center without good energy management and a data center with a well thought energy strategy. The goal of this comparison is to gain insight into the potential competitive advantage a data center can gain from an improved energy strategy.

3.2 Mathematical Form

In this section the mathematical descriptions are given for the calculations that are done to gain the results.

3.2.1 Effect of Energy Efficiency on Electricity Costs

$$Electricity\ cost_{PUE} = \sum_{y=0}^{t} Electricity\ cost_y/(1+r)^y$$

$$Electricity\ cost_y = Tot\ ElCo\ x\ p_y$$

With:

Tot ElCo = Total electricity consumption of a data center

p_y = price paid per MWh in year y

y = year: 2018-2027

3.2.2 Effect of Renewable Energy Projects on Electricity Costs

3.2.2.1 Levelized Cost of Electricity

The formula used to calculate the LCOE is:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

LCOE Levelized Cost of Electricity in EUR/kWh

I_0 Investment expenditure in EUR

A_t Annual total cost in EUR per year t

$M_{t,el}$ Produced amount of electricity in kWh per year

i Real interest rate in %

n Economic lifetime in years

t Year of lifetime (1, 2, ...n)

3.2.2.2 Net Present Value Calculation

$$NPV_{RP} = \sum_{y=0}^{t} Benefit/(1+r)^y - \sum_{y=0}^{t} Cost/(1+r)^y$$

Costs: Calculate the costs from the renewable energy project

y = year: 2018 - 2048

Year(0): Investment costs of renewable energy project

Year(1-30): O&M costs

r = discount factor

Benefits: Calculate the benefit gained from the reduction in electricity costs

Year(0): $Benefit = 0$

Year(1-30): $Benefit = Electricity\ cost_{NP} - Electricity\ cost_{RP}$

r = discount factor

Electricity costs:

$$Electricity\ cost_{NP} = \ Tot\ ElCo\ x\ p_y$$

$$Electricity\ cost_{RP} = (Tot\ ElCo - M_{t,el})\ x\ p_y$$

With:

Tot ElCo = Total electricity consumption of a data center

$p_y = price\ paid\ per\ MWh\ in\ year\ y$

$Electricity\ cost_{NP} = Electricity\ cost\ without\ RE\ project$

$Electricity\ cost_{RP} = Electricity\ cost\ with\ RE\ project$

$M_{t,el} = Produced\ amount\ of\ electricity\ in\ MWh\ per\ year$

3.2.3 Competitive Advantage Calculation

$$CA_Y = \ (EC_{Baseline,y} - \ EC_{PUE\ 1.09+PV\ 3,y}) + CA_{Y-1}$$

With:

CA_Y = Cumulative competitive advantage in year y (2024-2033)

Electricity costs (EC):

$$EC = \sum_{y=0}^{t} EC_y/(1+r)^y$$

$$EC_{Baseline} = \ Tot\ ElCo_{Baseline}\ x\ p_y$$

$$EC_{PUE1.09+PV3} = \left(Tot\ ElCo_{PUE\ 1.09}\ x\ p_y\right) + (M_{t,el}\ x\ LCOE_{PV3})$$

Tot ElCo = Total electricity consumption of a data center

r = discount factor

$M_{t,el} = Produced\ amount\ of\ electricity\ in\ MWh\ per\ year$

$p_y = price\ paid\ per\ MWh\ in\ year\ y$

$LCOE_{PV3}$ = Levelized cost of electricity of PV project 3

3.3 Data

3.3.1 Energy Models

3.3.1.1 Energy Consumption of Data Centers

In Avgerinou e.a. (2017), data is given about the total annual electricity consumption of 289 data centers participating in the Code of Conduct [4]. The total annual electricity consumption was 3 735 735 MWh, with an average annual electricity consumption of 13 684 MWh or 13.684 GWh per data center.

To create an energy price model for the data centers in Belgium, a data set of the total annual consumption of a street in Flanders for 2021 is used [33]. In this data set, a search was carried out to find the electricity consumption of 40 data centers located in Flanders. After an elimination step regarding the number of access points (e.g. buildings) per street, 13 streets remained. For these streets, the energy consumption of the data center can be estimated and are summarized in Table 1.

	Mean (in kWh)	Min (in kWh)	Max (in kWh)	Q1 (in kWh)	Q3 (in kWh)
13 data centers	10 706 250	2 794 049	40 663 687	4 533 344	12 959 733

Table 1: Electricity consumption data centers

From these numbers, it can be concluded that there are bigger data centers with an electricity consumption of approximately 12-13 GWh and smaller data centers with an electricity consumption of approximately 4-5 GWh. The simulations will be done for the bigger data centers.

3.3.1.2 Electricity Prices

The prices on the futures markets are used as the prices in the scenarios. The prices on the future markets are used to negotiate contracts in advance for the supply of electricity in the following days, quarters or years. These prices are less volatile than spot prices, meaning that energy-intensive companies can hedge their risks against price hikes and plan their electricity costs in a strategy.

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

Average price per MWh	€ 39.75	€ 52.54	€ 54.29	€ 43.06	€ 91.50	€ 266.66	€ 159.19	€ 136.14	€ 117.56	€ 97.12

Table 2: Electricity prices in Belgium 2018-2027[34]

For the simulation of the renewable energy strategies, estimations and assumptions must be made to determine the prices per MWh until 2043 and 2048. The assumptions and estimates are based on an analysis of Energy Brainpool [40]. Three scenarios are forecasted: Tension, Central and relief. The names of these scenarios describe the geopolitical development of Europe.

Average price in € per MWh	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
Relief	€ 82.15	€ 67.18	€ 52.20	€ 53.09	€ 53.98	€ 54.87	€ 55.76	€ 56.67	€ 57.10	€ 57.53
Central	€ 87.33	€ 77.54	€ 67.75	€ 68.42	€ 69.09	€ 69.76	€ 70.43	€ 71.10	€ 71.32	€ 71.54
Tension	€ 92.15	€ 87.18	€ 82.20	€ 84.66	€ 87.12	€ 89.58	€ 92.04	€ 94.50	€ 95.38	€ 96.26

Table 3: Electricity prices in Belgium 2028-2047[34]

Average price in € per MWh	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
Relief	€ 57.87	€ 58.30	€ 58.85	€ 59.90	€ 60.95	€ 62.00	€ 63.60	€ 65.20	€ 66.80	€ 68.40
Central	€ 71.76	€ 71.98	€ 72.20	€ 72.95	€ 73.70	€ 74.45	€ 74.89	€ 75.33	€ 75.77	€ 76.21
Tension	€ 97.14	€ 98.02	€ 98.90	€ 99.63	€ 100.36	€ 101.10	€ 102.21	€ 103.32	€ 104.43	€ 105.54

Table 3: Electricity prices in Belgium 2038-2048[34]

Average price in € per MWh	2048
Relief	€ 70.00
Central	€ 76.65
Tension	€ 106.65

Table 3: Electricity prices in Belgium 2038-2047[34]

3.3.1.3 Power Usage Effectiveness (PUE)

The PUE value gives data centers a better understanding of their energy efficiency. It is calculated by the ratio of total facility power to IT equipment power [4]. A higher PUE value means a less energy efficient data center. The PUE value of 1.8 is based on the average given by Avgerinou e.a. (2017) [4]. The second value of 1.25 can be connected to the data center of LCL. LCL is an independent Belgian data center company with sustainability and efficiency as one of its general objectives [35]. The final value of 1.09 is linked to the Google data center of Saint-Ghislain, one of Google's most sustainable data centers [36].

3.3.2 Renewable Energy Strategies

3.3.2.1 Photovoltaic (PV)

For the PV-systems, three projects will be simulated. A project with a generation of 100 kWp, a project with a generation of 1 MWp and a project with a generation of 2.5 MWp.

The inspiration for the first project is a rooftop PV-system of approximately 450 m² (250 panels with 415 Wp) [38]. The second project is inspired by the solar panel park of LCL [39]. The LCL solar panel park can produce 1 MWp with 2000 panels. Based on the data used in this simulation, a PV-system of 4 338 m² (2410 panels) will be needed to produce 1 MWp [38]. The third project is inspired by Google's Belgian on-site solar project [36]. This solar plant produces 2.8 MWp with 10 665 panels. In this simulation, a PV-system of 10 845 m² (6025 panels) will be used to produce 2.5 MWp [38].

To calculate the LCOE of these strategies, the values of the variables have to be set [37][38][30]:

- Investment expenditure in EUR[1]:
    - Project 1: 750 – 1400 EUR/kWp
    - Project 2 & 3: 530 – 800 EUR/kWp
        - Project 2: 665 – 800 EUR/kWp
        - Project 3: 530 – 665 EUR/kWp
- Annual total cost in EUR per year t[2]:
    - 16.64 EUR/kW
- Produced amount of electricity in kWh per year[3]:

[1] The data in Kost e.a. (2021) suggested price ranges of 750-1400 and 530-800, but this is for cristalline modules (mostly 215 Wp) [37]. The data from VEKA also implies installation costs of 1398 (1145+250) for roof panels with 415 Wp [7]. The assumption is made that for larger projects on the ground the installation price will reduce like suggested in Kost e.a.

[2] Based O&M costs assumptions from IRENA (2021). Converted to EUR with 1 USD = 0.9141 EUR.

[3] These calculations are based on estimations from VEKA [38].

    - Project 1: (250 panels x 415 Wp) = 103 542 kWh/year
    - Project 2: (2410 panels x 415 Wp) = 997 870 kWh/year
    - Project 3: (6025 panels x 415 Wp) = 2 494 674 kWh/year
- Real interest rate in %:
    - 4.9%
- Economic lifetime in years:
    - 30

3.3.2.2 Wind Energy

With the available data about the costs for a wind power plant (WPP), it is possible to set up a large WPP with a 2 MW turbine [30].

To calculate the LCOE of this strategy, the values of the variables have to be set [37][30]:

- Investment expenditure in EUR:
    - 1400 – 2000 EUR/kW
- Annual total cost in EUR per year t:
    - 44.79 EUR/kW
- Produced amount of electricity in kWh per year:
    - 1800 FLH: 1800 x 2 000 kW = 3 600 000 kWh/year
        - Sensitivity: 1100 – 2500 FLH
- Real interest rate in %:
    - 4.9%
- Economic lifetime in years:
    - 25

4 Results

4.1 Effect of the Price Shock on the Electricity Costs of Data Centers

4.1.1 Effect of the Price Shock on the Baseline

The electricity costs of a data center are heavily dependent on the electricity price on the market, as it is the only variable on which the data center operators have no influence. According to the data, the electricity price shock started in 2022 with an increase of 212.49%.

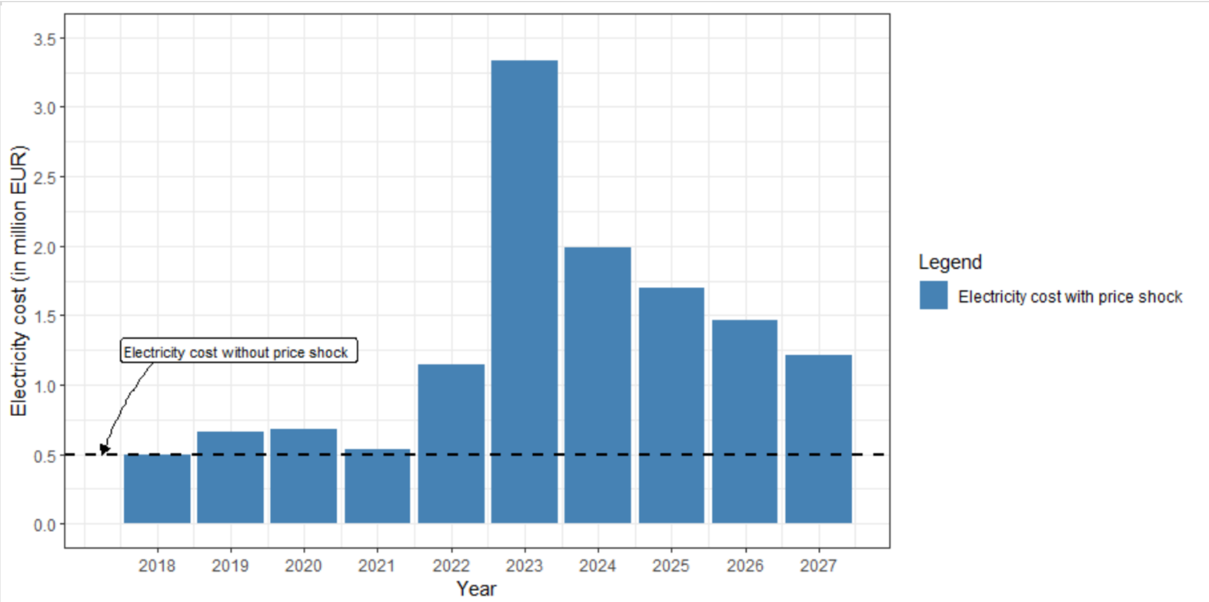

Figure 2 Effect price shock with PUE 1.8

The results in Figure 2 shows that after the price shock in 2022, the yearly electricity costs of a data center with a yearly energy consumption of 12.5 GW increased above €1,000,000. With a peak in 2023 of €3,333,250 that is equal to an increase of 670.84%. Over a period of ten years, the price shock could add a total of €5,941,579 to the electricity costs, this comes down to a growth of 254.11%. Before the price shock, the energy costs of a data center with an annual consumption of 12.5 GW did not exceed the threshold of €750,000. Since the price shock in 2022, the energy cost has exceeded €1,000,000 and it is not expected to decrease to the previous level before 2027.

4.1.2 Effect of Improved Energy Efficiency on the Electricity Costs

A variable in which a data center operator might have an influence is the yearly energy consumption of the data center. To achieve a reduction in yearly energy consumption, data centers can invest in best practices that reduce the PUE.

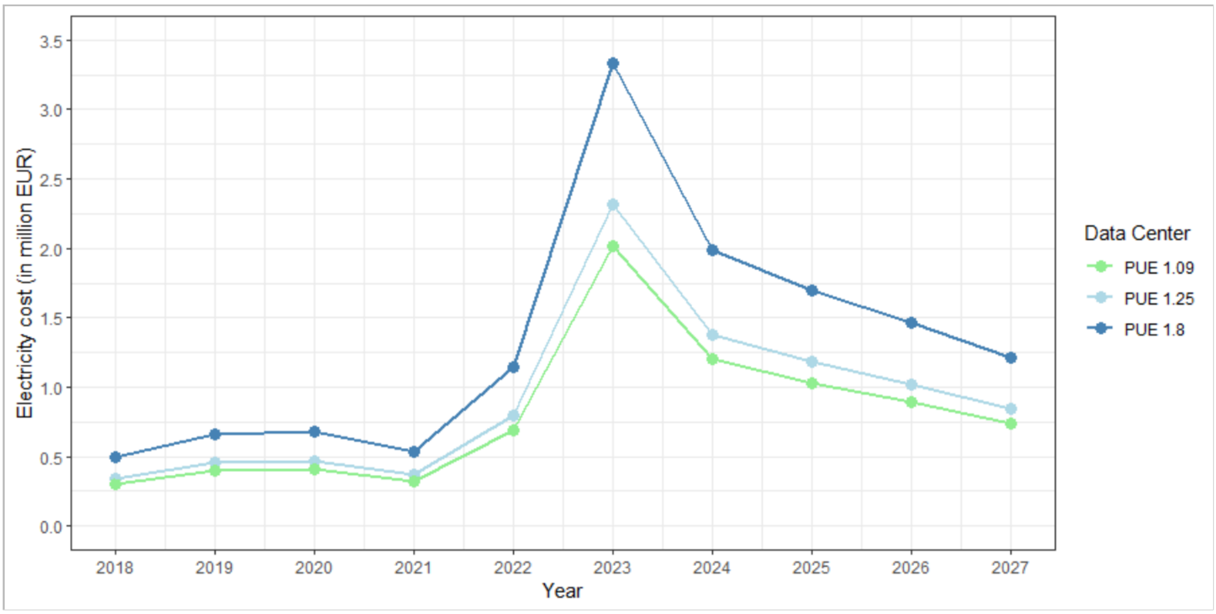

Figure 3 Benefit of Energy efficiency during price shock

Data centers that invested in energy efficiency before the price shock gained significant benefits from these expenses, as shown in Figure 3. At the peak of the price shock in 2023 a reduction in costs of €1,018,491.87 and €1,314,783.13 occurred for the data centers with a PUE of 1.25 and 1.09 respectively. The total savings that the expenses related to energy efficiency could realize over a 10-year period are €2,993,529.56 for a PUE of 1.25 and €3,864,382.34 for a PUE of 1.09.

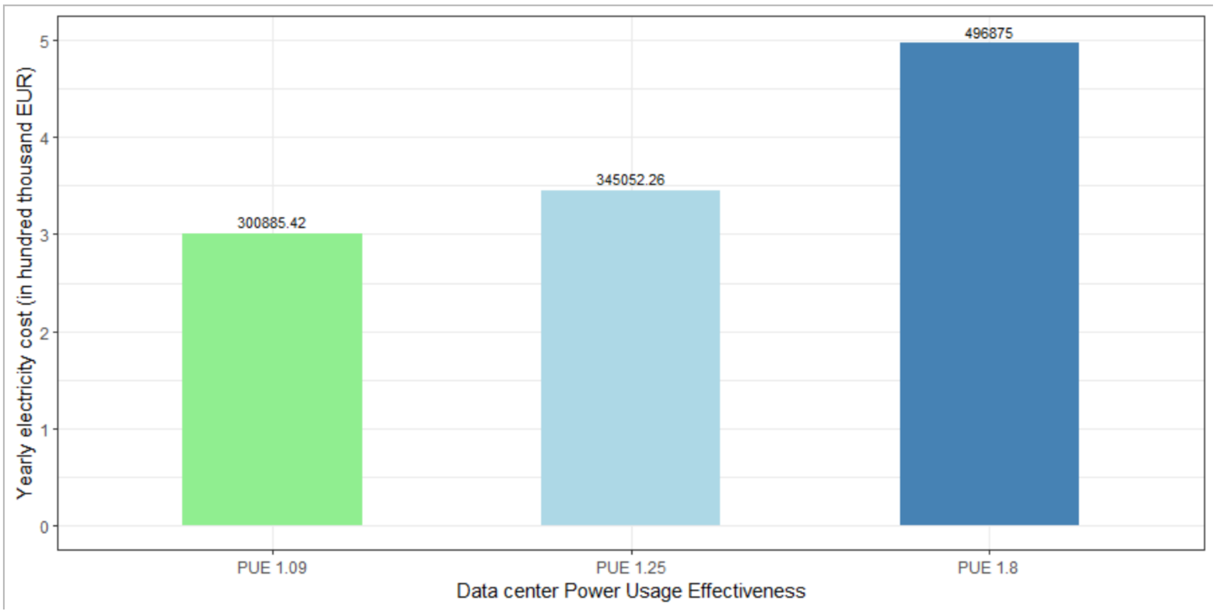

Figure 4 Yearly cost of electricity without price shock

Even when there would be no price shock, the results show that yearly savings of €151,822.74 and €195,989.58 can be gained.

4.2 Effect of Renewable Energy Projects on Electricity Costs

4.2.1 Comparison of Renewable Energy Projects with LCOE

The method of Levelized Cost of Electricity (LCOE) enables a comparison to be made between power plants that have varying generation and cost structures [37]. Table 4 shows the LCOE of each project. These results show that PV projects 2 and 3 have the lowest LCOE. Even though PV project 1 has the lowest investment cost of € 124,500.00, the ratio to the amount of electricity produced is smaller than the other projects resulting in the project with the highest LCOE. During the price shock and times of uncertainties in the markets, the LCOEs of the projects are all lower than the market price. When looking further into the price scenarios given in the data section, two projects offer an advantage in every scenario project 2 and project 3.

	PV Project 1	PV Project 2	PV Project 3	Wind Project
LCOE (in EUR per kWh)	0.0693	0.0471	0.0384	0.0664

Table 4: LCOE Projects

4.2.2 Sensitivity Analysis LCOE

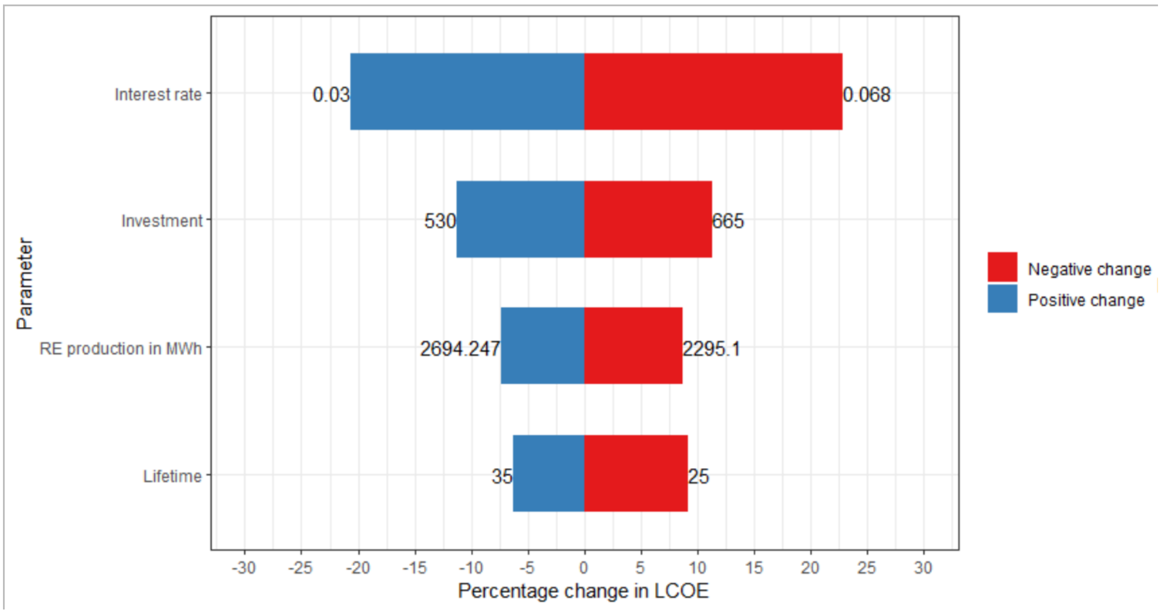

Figure 5 Sensitivity analysis LCOE PV project 3

Figure 7 highlights the primary findings regarding the sensitivity of the parameters of the LCOE. The analysis reveals that the investment cost and the level of renewable energy production demonstrate the highest sensitivity, with a sensitivity coefficient of around one. Additionally, the LCOE is notably influenced by the interest rate and the project's lifetime, demonstrating significant sensitivity to changes in these factors. These results emphasize the critical role investment costs, renewable energy production levels, interest rates, and project lifetimes play in determining the LCOE. The maintenance cost is left out because the changes were insignificant.

4.2.3 Cost-Benefit Calculation of Renewable Energy Projects

The results from the cost-benefit calculation show that all the projects have a positive net present value and are given in Table 4. Even though results from Table 4 showed significant differences in the LCOE between the RE projects, the NPVs of all the projects are positive. PV project 3 and the wind project have the highest present values, this can be linked to the higher electricity production. During the price shock, less electricity has to be bought at the high market prices. PV project 3 has a yearly electricity production of 2.5 GW and the wind project has a yearly electricity production of 3.6 GW. To produce this amount of electricity a higher investment is needed of € € 1,490,567.72 and € 3,400,000.00 respectively.

	PV Project 1	PV Project 2	PV Project 3	Wind Project
NPV (Relief)	€ 22,350.92	€ 559,413.04	€ 1,735,701.15	€ 940,465.02
NPV (Central)	€ 33,251.68	€ 664,469.45	€ 1,998,342.07	€ 1,276,954.17
NPV (Tension)	€ 51,531.46	€ 840,641.38	€ 2,438,771.70	€ 1,777,342.30

Table 5: NPV Projects

The NPVs of the projects increase in situations when the electricity price on the market increases. The electricity price and the amount of electricity produced are the variables that influence the benefits of the projects. In order to address uncertainties surrounding the acceptance of these projects and account for situations where it may not be feasible to achieve the maximum capacity of the power plants, the levels are calculated where the NPVs become break-even.

Figure 5 gives the benefits and costs of PV project 3 under the 'Relief' price scenario. When the power plant produces more than 47% of its maximum capacity, the NPV remains positive. This percentage decreases towards 38% during the 'Tension' price scenario.

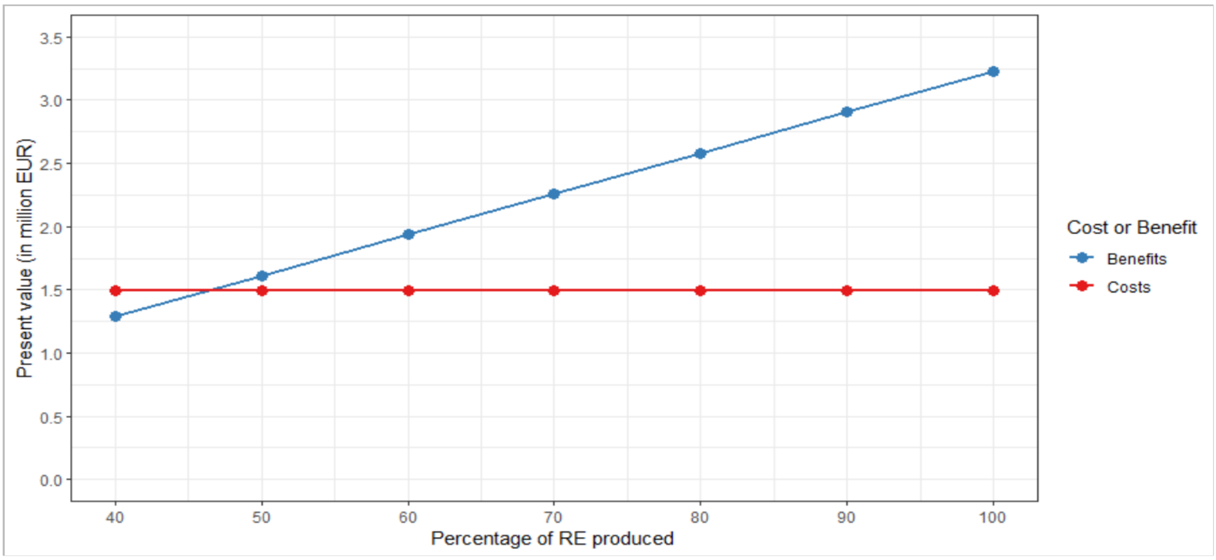

Figure 6 Break-even calculation PV project 3

The percentage of renewable energy produced when the NPV of PV project 2 becomes neutral is 57%, and 47% during the 'Tension' price scenario. For PV project 1 these values are higher. Under the 'Relief' price scenario the NPV becomes neutral when approximately 83% of the maximum capacity is produced, this becomes 69% in the highest price scenario. The minimal production levels for the wind project are 78% and 65%.

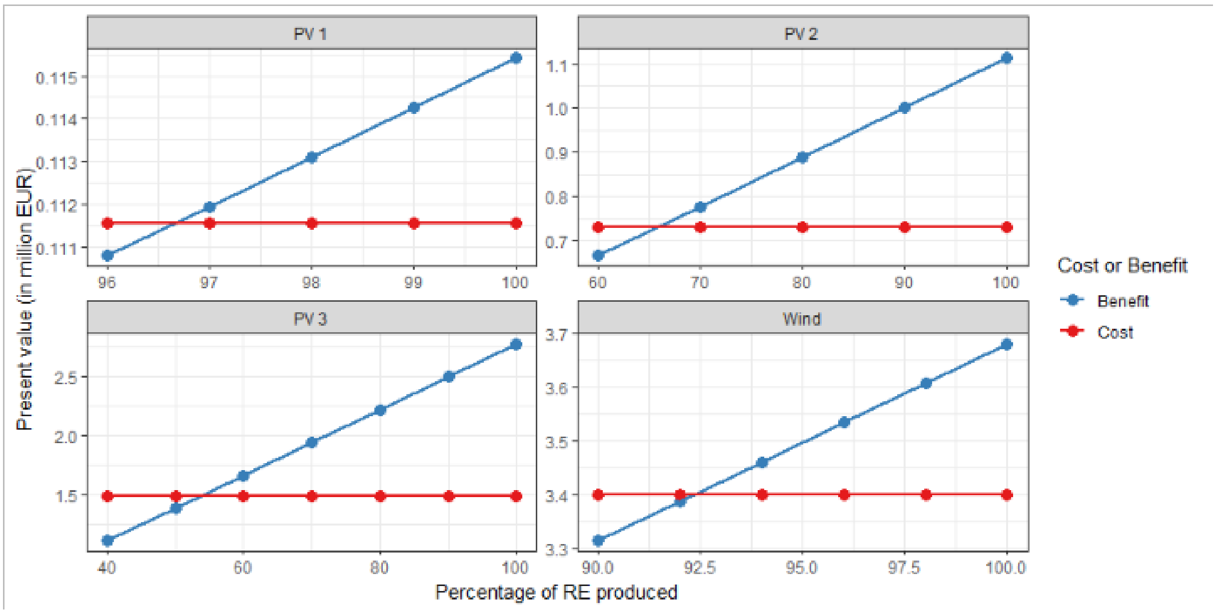

Figure 7 Cost and Benefits of RE projects starting in 2024

If data center operators decide to invest in renewable energy projects after this year, it can still be beneficial. Under the 'Relief' price scenario, all the renewable energy projects have a positive NPV if they decide to invest in a renewable energy project in 2024. In Figure 5, the break-even points are depicted, representing the thresholds at which an investment in the renewable energy project would not yield a worthwhile return. Notably, for PV project 1 and the wind project, these break-even points occur at less than ten percent of their respective maximum capacities.

4.3 Competitive Advantage of Energy Efficiency and RE project

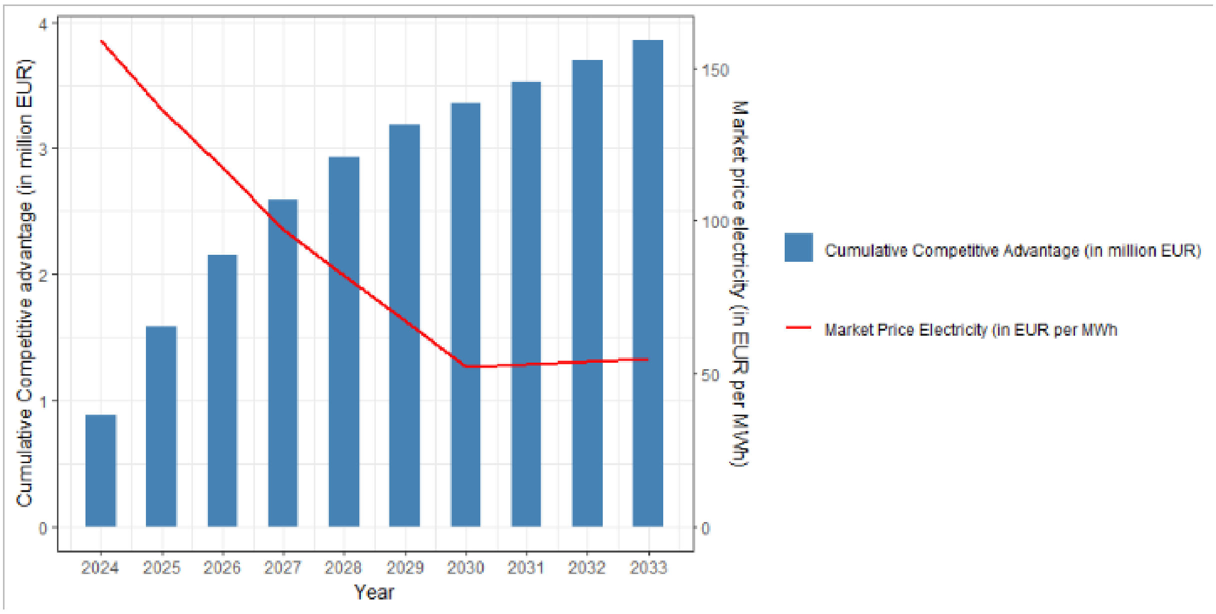

Figure 8 Evolution of competitive advantage of a data center with PUE 1.09 and PV project 3 in comparison with the baseline in relation to the market price in the period from 2024-2033.

Investments in energy efficiency and renewable energy projects can deliver significant benefits as the previous results show. Figure 6 shows the cumulative gain in competitive advantage that a data center with a PUE of 1.09 and PV project 3 can yield in comparison to the baseline over a period of ten years. Even with an expected declining energy price of the 'Relief' price scenario, the competitive advantage becomes € 3,858,788.91, and continues to rise at a price slightly above € 60 /MWh.

5 Discussion

The energy price shock has a significant impact on the cost structure of a data center. As discussed in section 2.1, the electricity costs of a data center can amount to 50% of the operating costs [13][14]. At the peak in 2023, the electricity price on the forward market was 670.84% higher than in 2018. This shifted the weight of the electricity costs to an even greater amount than the assumed 50%.

The overall increase in operating costs due to the energy price shock will influence data centers negatively in the short term. As the costs incurred for delivering the services increases, the budgeting and pricing structures must change to cover the costs. Data centers will have to pass on the increased energy costs to their customers. This may be a way to handle the price shock in the short term, but it is expected that the electricity costs will remain at a higher level as the results show. The higher electricity will potentially become a long-term burden. To mitigate these effects in the long term, data centers have to implement measures to manage their energy costs. Investments in energy efficiency practices have to be made to decrease the total energy consumption of the data center. Practices, as described in the EU Code of Conduct for energy efficiency in data centers, can help reduce energy consumption while maintaining or even improving performance [19].

Energy efficiency practices will improve the financial sustainability of a data center. By maximizing energy efficiency, long-term cost optimization can be achieved. With the comparison of data centers with different PUE, the previous statement is proven. Data centers could have saved more than a million euros during the price shock. And even if the price shock did not occur, a significant yearly benefit could have been gained. During the price shock, data centers that had not prioritized energy efficiency found themselves at a significant disadvantage, while those with lower PUE gained a competitive advantage. The substantial increase in energy costs could act as a catalyst for long-term transformations within the industry. This event compelled data centers to recognize the importance of energy efficiency.

Another strategy that could lower the weight of the electricity costs is on-site renewable energy production. On-site renewable energy projects offer several benefits for data centers. On-site renewable energy projects like a PV plant or a wind turbine offer long-term cost savings. The LCOE is a valuable metric to consider when evaluating and planning investments in renewable energy projects. By comparing the LCOE of a project with electricity price forecasts in the market, one can assess the feasibility and viability of the investment. This helps determine whether an investment in the project would be worthwhile. The findings indicate that all four proposed projects offer cost advantages compared to the electricity price in the market. The cost-benefit analysis confirms the claim that investing in renewable energy projects is beneficial, particularly during periods of uncertainty in the electricity market. These projects contribute to reducing dependence on grid-supplied energy, mitigating the impact of unforeseen increases in electricity prices by reducing the need to purchase additional electricity from the market.

The sensitivity analysis highlights the significance of conducting a thorough assessment before investing in an on-site renewable energy project. Factors such as investment cost and energy production play a crucial role in determining the potential benefits of the project. Specifically, in the case of the suggested projects in this research, PV project 1 and the wind project demonstrate that less favorable parameters can quickly result in increased costs. Based on the results, it appears that starting an on-site generation strategy with large photovoltaic projects, such as PV project 3, is currently a more favorable option because of greater economies of scale. Thus, before implementing and investing in a renewable energy strategy it is suggested that an in-depth study is carried out.

The implementation of energy efficient measures and the integration of on-site renewable energy could mitigate the impact of the price shock on data centers. Data centers that had already prioritized energy efficiency and had initiated renewable energy projects prior to the occurrence of the price shock gained a significant competitive advantage over their competitors. Despite the anticipation of a decrease and stabilization in electricity prices, investments in energy efficiency and renewable energy continue to be crucial for effective risk management and strategic planning. The findings indicate that a data center with improved energy efficiency and a renewable energy project can gain a significant competitive advantage even when uncertainties in the electricity market are reduced.

Next to financial gains data centers that generate their own renewable energy can effectively showcase their commitment to sustainability, attracting environmentally conscious customers and stakeholders, and aligning their brand with green initiatives.

6 Conclusion

The electricity market's price shock has substantial implications for Belgian data centers, particularly in terms of operational costs. The occurrence of a price shock significantly impacts a data center's operational expenses, with electricity costs being the dominant factor. Data centers are in need of a constant power supply, highlighting the importance of a stable and cost-effective power supply. Energy management has to be a main activity in the management of a data center, as the amount of energy bought on the market determines the impact of the price shock on the data center.

The first subject for energy management is to reduce the electricity consumption of the data center. There are best practices available for energy efficiency, as exemplified by the Code of Conduct established by the European Union. Potential improvements in IT equipment, Cooling, and Power Supply are suggested. As the overall structure of data centers can differentiate a lot, conducting an energy audit enables data centers to gain a comprehensive understanding of their energy consumption patterns and identify areas of improvement. These improvements can potentially reduce electricity consumption significantly, reducing the weight of electricity costs. This is crucial when electricity prices become less stable.

Another subject is to lower the dependence on the energy of the grid. Investments in on-site renewable energy projects offer a promising avenue with significant benefits. Implementing renewable energy projects allows data centers to reduce the amount of energy purchased from the market. As a result, this reduces the impact of potential future electricity price increases. In these projects, it is important that they are set up in the right way, as parameters like the investment cost and the amount of energy produced can influence the value of the project. Differences in benefits and flexibility are visible in the projects suggested in this research. Thus, making it clear that a well-thought exercise is needed before investing in a renewable energy project. As not every project will gain the same benefits and may even incur extra costs. By carefully evaluating these parameters and their potential impact on the project's outcomes, stakeholders can make informed decisions about the feasibility and profitability of the renewable energy investment. This assessment helps identify the key variables that can significantly influence the project's financial performance, allowing for better risk management and strategic planning.

Furthermore, data centers that proactively invest in energy management in the form of energy efficiency and renewable energy project are positioned to gain a significant competitive advantage. By reducing the PUE, reducing energy waste, and generating renewable energy on-site, data centers can achieve cost savings and operational efficiency. This advantage becomes even more prominent in an uncertain electricity market with volatile prices. With a proactive energy management approach, data centers can better control their operational costs and differentiate themselves from competitors. Integrating energy efficiency practices and renewable energy projects is a strategic approach that enables data centers to thrive in an increasingly competitive environment.

7 Assumptions and Limitations

A first assumption is made in the setup of the energy model of the data center. The energy model is primarily based on information found in the literature and supported by data analyses of raw data from Fluvius. This introduced the limitation that the energy consumption of the data center is given on a yearly basis and remains the same each year. The model is not able to give a representation of the energy consumption of each type of equipment, e.g. IT equipment, cooling equipment. The constant yearly display of energy consumption makes the model not capable of showing fluctuations in consumption during the year, e.g. effects of weather.

Another assumption comes into play when implementing renewable energy projects in the cost-benefit calculation. It is assumed that all the energy that the plant produces can be used in the data center and thus substitutes for the amount of energy bought. In reality, this may not always be the case as it can be possible that the output by the plant at a given moment is higher than the consumption of the data center at that exact moment. A limitation that comes with this assumption is that the real benefits of the projects may be lower than suggested in this research, affecting their net present value. In practical renewable energy projects, it is important to consider the possibility of producing more energy than is consumed at certain times. This raises the question of how to effectively utilize the excess energy.

For the costs associated with changes in PUE, clear assumptions could not be made. The reason for this is that the costs can differ enormously for each data center. Sometimes a small change in equipment can cause a significant change in energy use and in some cases the change introduces much higher costs. This presents a limitation in the results of the energy efficiency models but can be solved by a well-executed energy audit in the data center.

A limitation that may potentially influence the result is that a simplified representation of the energy price is used in the models. The assumption is made that data centers are energy-intensive companies that buy their electricity on the forward market. In this market, individual contracts are set up with energy suppliers and can vary from the averages given on the Internet. Another factor that may influence the energy price is the usage of renewable energy. This will potentially influence the contracts that data centers currently have with their suppliers for several reasons. The amount of energy bought from the suppliers will be lower and most of the energy will be bought at times the energy price is the highest when there is no production of renewable energy.

A last limitation is that there was no data available to add a revenue model to study the impact of the price shock on the earnings of a data center.

8 References

[1] Zakeri, B., Paulavets, K., Barreto-Gomez, L., Echeverri, L. G., Pachauri, S., Boza-Kiss, B., Zimm, C., Rogelj, J., Creutzig, F., Ürge-Vorsatz, D., Victor, D. G., Bazilian, M. D., Fritz, S., Gielen, D., … Pouya, S. (2022). Pandemic, War, and Global Energy Transitions. *Energies*, *15*(17), 6114. https://doi.org/10.3390/en15176114

[2] *Impact of Russia's invasion of Ukraine on the markets: EU response*. (z.d.). Retrieved from https://www.consilium.europa.eu/en/policies/eu-response-ukraine-invasion/impact-of-russia-s-invasion-of-ukraine-on-the-markets-eu-response/

[3] Calanter, P., & Zisu, D. (2022). EU Policies to Combat the Energy Crisis. *Global Economic Observer*, *10*(1), 26–33. http://www.proquest.com/docview/2678518985/abstract/38105F62D9C4BB4PQ/1

[4] Avgerinou, M., Bertoldi, P., & Castellazzi, L. (2017). Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency. *Energies*, *10*(10). https://doi.org/10.3390/en10101470

[5] Dayarathna, M., Wen, Y., & Fan, R. (2016). Data Center Energy Consumption Modeling: A Survey. *IEEE Communications Surveys & Tutorials*, *18*(1), 732–794. https://doi.org/10.1109/COMST.2015.2481183

[6] Gu, C., Fan, L., Wu, W., Huang, H., & Jia, X. (2018). Greening cloud data centers in an economical way by energy trading with power grid. *Future Generation Computer Systems*, *78*, 89–101. https://doi.org/10.1016/j.future.2016.12.029

[7] Flucker, S., & Tozer, R. (2013). Data Centre Energy Efficiency Analysis to minimize total cost of ownership. *Building Services Engineering Research & Technology*, *34*(1), 103–117. https://doi.org/10.1177/0143624412467196

[8] Chiaraviglio, L., D'Andreagiovanni, F., Lancellotti, R., Shojafar, M., Blefari-Melazzi, N., & Canali, C. (2018). An Approach to Balance Maintenance Costs and Electricity Consumption in Cloud Data Centers. IEEE Transactions on Sustainable Computing, 3(4), 274–288. https://doi.org/10.1109/TSUSC.2018.2838338

[9] Hameed, A., Khoshkbarforoushha, A., Ranjan, R., Jayaraman, P. P., Kolodziej, J., Balaji, P., Zeadally, S., Malluhi, Q. M., Tziritas, N., Vishnu, A., Khan, S. U., & Zomaya, A. (2016). A survey and taxonomy on energy efficient resource allocation techniques for cloud computing systems. Computing, 98(7), 751–774. https://doi.org/10.1007/s00607-014-0407-8

[10] Chen, S., Irving, S., & Peng, L. (2016). Operational Cost Optimization for Cloud Computing Data Centers Using Renewable Energy. IEEE Systems Journal, 10(4), 1447–1458. https://doi.org/10.1109/JSYST.2015.2462714

[11] Celestine, A.-D. N., Link to external site, this link will open in a new window, Sulic, M., Wieliczko, M., & Stetson, N. T. (2021). Hydrogen-Based Energy Storage Systems for Large-Scale Data Center Applications. Sustainability, 13(22), 12654. https://doi.org/10.3390/su132212654

[12] Liu, X., Hou, G., Yang, L., & Link to external site, this link will open in a new window. (2022). Dynamic Combined Optimal Scheduling of Electric Energy and Natural Gas Energy Consumption in Data Center. Discrete Dynamics in Nature and Society, 2022. https://doi.org/10.1155/2022/3917170

[13] Keskin, I., & Soykan, G. (2022). Optimal cost management of the CCHP based data center with district heating and district cooling integration in the presence of different energy tariffs. Energy Conversion and Management, 254, 115211. https://doi.org/10.1016/j.enconman.2022.115211

[14] Laganà, D., Mastroianni, C., Meo, M., Link to external site, this link will open in a new window, Renga, D., & Link to external site, this link will open in a new window. (2018). Reducing the Operational Cost of Cloud Data Centers through Renewable Energy. Algorithms, 11(10), 145. https://doi.org/10.3390/a11100145

[15] Shi, L., Shi, Y., Wei, X., Ding, X., & Wei, Z. (2017). Cost Minimization Algorithms for Data Center Management. IEEE Transactions on Parallel and Distributed Systems, 28(1), 60–71. https://doi.org/10.1109/TPDS.2016.2549016
[16] Xie, Y., Cui, Y., Wu, D., Zeng, Y., & Sun, L. (2021). Economic analysis of hydrogen-powered data center. International Journal of Hydrogen Energy, 46(55), 27841–27850. https://doi.org/10.1016/j.ijhydene.2021.06.048
[17] Tozer, R., Flucker, S., & Whitehead, B. (2016). The Case for Sustainability in Data Centers. ASHRAE Transactions, 122, 99–110.
[18] Zhang, Y., Link to external site, this link will open in a new window, & Liu, J. (2022). Prediction of Overall Energy Consumption of Data Centers in Different Locations. Sensors, 22(10), 3704. https://doi.org/10.3390/s22103704
[19] European Commission. European Code of Conduct on Data Centre Energy Efficiency. Version 3.3.0. Available online: https://e3p.jrc.ec.europa.eu/sites/default/files/documents/publications/jrc124057_jrcjrc124057_european_code_of_conduct_on_data_centre_energy_efficiency_final_1.pdf (accessed on 17 February 2023)
[20) Rong, H., Zhang, H., Xiao, S., Li, C., & Hu, C. (2016). Optimizing energy consumption for data centers. Renewable and Sustainable Energy Reviews, 58, 674–691. https://doi.org/10.1016/j.rser.2015.12.283
[21] Oró, E., Depoorter, V., Garcia, A., & Salom, J. (2015). Energy efficiency and renewable energy integration in data centres. Strategies and modelling review. Renewable and Sustainable Energy Reviews, 42, 429–445. https://doi.org/10.1016/j.rser.2014.10.035
[22] Directorate-General for Internal Market, I., Intertek PLC, Wood, J., Wu, A., Fernandes, S., Brocklehurst, F., McAlister, C., & Harrison, B. (2016). Ecodesign technical assistance study on standards for lot 9 enterprise servers and enterprise data storage: Final report. Publications Office of the European Union. https://data.europa.eu/doi/10.2873/782959
[23] Beaty, D. L., Quirk, D., & Morrison, F. T. (2019). Liquid-Cooling Trends In Data Centers. ASHRAE Journal, 61(7), 56–62.
[24] Dinesh Reddy, V., Setz, B., Subrahmanya V.R.K. Rao, G., Gangadharan, G. R., & Aiello, M. (2018). Best Practices for Sustainable Datacenters. IT Professional, 20(5), 57–67. https://doi.org/10.1109/MITP.2018.053891338
[25] Koronen, C., Åhman, M., & Nilsson, L. J. (2020). Data centres in future European energy systems—Energy efficiency, integration and policy. Energy Efficiency, 13(1), 129–144. https://doi.org/10.1007/s12053-019-09833-8
[26] Sovacool, B. K., Monyei, C. G., & Upham, P. (2022). Making the internet globally sustainable: Technical and policy options for improved energy management, governance and community acceptance of Nordic datacenters. Renewable and Sustainable Energy Reviews, 154, 111793. https://doi.org/10.1016/j.rser.2021.111793
[27] CREG. Studie over de stijging van de elektriciteits- en aardgasprijzen in België. (F)2289. Available online: https://www.creg.be/sites/default/files/assets/Publications/Studies/F2289NL.pdf (accessed on 17 February 2023)
[28] CREG. Studie over de elektriciteitsbelevering van grote industriële klanten in België in 2021. (F)2443. Available online: https://www.creg.be/sites/default/files/assets/Publications/Studies/F2443NL.pdf (accessed on 17 February 2023)
[29] Data Centers: Belgian Site Adds Solar. (z.d.). Google Sustainability. Available online: https://sustainability.google/progress/projects/belgium-solar/ (accessed on 17 februari 2023)
[30] IRENA. Renewable Power Generation Costs in 2021. Available online: https://www.irena.org/Publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021 (accessed on 17 February 2023)
[31] Minister De Sutter wil dat datacenters minder energie gaan verbruiken. (z.d.). accessed on 10 April 2023, van https://trends.knack.be/kanaal-z/z-nieuws/minister-de-sutter-wil-dat-datacenters-minder-energie-gaan-verbruiken/

[32] BIPT publiceert studie over datacentra en aanbieders van digitale inhoud in België | BIPT. (z.d.). accessed on 10 April 2023, van https://www.bipt.be/consumenten/publicatie/bipt-publiceert-studie-over-datacentra-en-aanbieders-van-digitale-inhoud-in-belgie
[33] Dataroom Fluvius (2022) Verbruiksgegevens per straat. accessed on 8 April 2023, van https://opendata.fluvius.be/explore/dataset/1_03-verbruiksgegevens-op-straatniveau/information/
[34] Actuele ontwikkeling elektriciteitsprijzen. (z.d.). Zicht op Energie. accessed on 8 April 2023, van https://zichtopenergie.nl/prijsontwikkelingen/ontwikkelingen-electriciteitsprijzen/
[35] LCL. (2021). LCL neemt datacenter van ENGIE Solutions over, beschikt zo over eerste datacenter in Wallonië. accessed on 9 April 2023, van https://www.lcl.be/nl/nieuws/lcl-neemt-datacenter-van-engie-solutions-over-beschikt-zo-over-eerste-datacenter-in-wallonie/
[36] Data Centers: Belgian Site Adds Solar. (z.d.). Google Sustainability. accessed on 17 Februari 2023, van https://sustainability.google/progress/projects/belgium-solar/
[37] Kost, C., Shammugam, S., Fluri, V., Peper, D., Memar, A. D., & Schlegl, T. (2021). LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES
[38] VEKA. (z.d.). accessed on 5 April 2023, van https://apps.energiesparen.be/zonnekaart
[39] LCL. (z.d.). LCL neemt datacenter van ENGIE Solutions over, beschikt zo over eerste datacenter in Wallonië. accessed on 9 April 2023, van https://www.lcl.be/nl/nieuws/lcl-neemt-datacenter-van-engie-solutions-over-beschikt-zo-over-eerste-datacenter-in-wallonie/
[40] Schmitt, A. (2022, april 11). EU Energy Outlook 2050: How will the European electricity market develop over the next 30 years? Energy BrainBlog. https://blog.energybrainpool.com/en/eu-energy-outlook-2050-how-will-the-european-electricity-market-develop-over-the-next-30-years/