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Abstract

The growing demand for data storage and computational power has increased the global deployment of data centers. Today, data centers are the backbone of modern companies, but also main consumers of energy and among the major producers of greenhouse gas emissions. Therefore, the development and implementation of sustainable and energy efficient Green Data Centers (GDC) has gained relevance from a scientific and practical point of view. Even though technological progress has revealed opportunities for improvements in energy efficiency, little effort has been made regarding the business case of GDC. In this paper, we analyze the coherence of economic and environmental objectives of GDC investments by conceptualizing a decision model using traditional financial metrics and by applying the model on exemplary data. We analyze both costs and realized energy savings associated with the GDC investment. Besides, we examine the influence of volatile energy prices on the investment decision. By integrating risk and return into one decision calculus, we determine the optimal GDC investment budget which reconciles long-term economic and environmental objectives. Our theoretical findings are supported by an application example of a GDC investment project. We hereby demonstrate the structural under-investment when disregarding volatile energy prices in decision-making.

Keywords: Sustainability, Green IT/IS, Green Data Centers, Energy efficiency.

1 Introduction

The continuing growth of information systems (IS) has been a major factor for the global increase of energy consumption and carbon dioxide emissions, leaving a carbon footprint that accelerates global warming. According to GeSI (2013), the IS industry accounts for almost 2% of global greenhouse gas emissions, which exceeds by far its share of global GDP. In order to reduce its carbon footprint, the development and implementation of energy efficient IS remains a key challenge for both science and practice. From a scientific point of view, considerable progress in the field of Green IS[1] innovations for environmental sustainability has been achieved in recent years (Melville, 2010). However, even though sustainable IS has been much talked about in research for several years, it has only just recently reached a maturity stage which triggered its rising use in practice (Fujitsu, 2012). This increase of acceptance is not only based on reinforced environmental awareness, but also because sustainable IS can significantly reduce energy costs which had been predicted to make up 50% of all IT-related costs (Gartner, 2006).

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[1] Watson et al. (2010) distinguish between Green IT (energy efficient equipment utilization of IT) and the broader spectrum of Green IS (design and implementation of IS that support sustainable business processes). In the following, we consider Green IT to be a proper subset of Green IS.

One area that has long been recognized as a major contributor to energy dissipation of IS, but which is now regarded as a key factor in creating a low-carbon IS infrastructure is *Green Data Centers (GDC).* Only in 2008, worldwide data centers combined emitted as much carbon dioxide as all of Argentina (Kaplan et al., 2008). Today, Gartner (2012) regard extreme low-energy servers as one of the top technologies that will be strategic for organizations. Following various studies regarding GDC, even low-investment measures for existing data centers like optimizing data storage or uninterrupted power supply (UPS) can quickly reduce energy consumption by 20% (BMU, 2008). More cost-intensive investments like innovative cooling concepts or the optimization of ventilation can further increase energy efficiency. These technological opportunities are accompanied by an ever increasing demand for server-side computing power due to the rapid growth of cloud computing and innovative IT solutions offered by concepts like "Infrastructure as a Service" (IaaS) or "Software as a Service" (SaaS) (Armbrust et al., 2010). Accordingly, the implementation of GDC is of utmost importance for companies to compete and to grow in the dynamic IS business environment.

While much research deals with the technical development and environmental impact of GDC, the business perspective is widely neglected in IS literature. As a consequence, CIOs still lack guidelines for planning and justifying the business case of GDC (Haanaes et al., 2011). We attempt to close this gap by analyzing the relationship between economic profit and environmental performance. At this, we develop a decision model that assesses the economic value of an ecologically advantageous data center, i.e. GDC, investment. We thereby contribute to existing literature by evaluating the impact of the investment with traditional financial metrics under consideration of volatile energy prices. We apply the decision model on exemplary data of a GDC investment project in combination with real-world energy prices. Based on this evaluation, the theoretical findings on the optimal GDC investment budget that promotes energy efficiency while avoiding unprofitable over-investment are confirmed from an application perspective. Bearing this in mind, we examine the following research question: *What is the optimal GDC investment budget that reconciles both environmental and economic objectives?*

Based on literature, we postulate three requirements which we deem relevant for assessing GDC investments. In order to create a quantifiable basis for the decision-making, we examine long-term cash flows of the GDC investment by means of decision theory. In doing so, we holistically consider the cost perspective as well as the returns on investment. By scrutinizing the future development of energy prices, we can further derive findings on the impact of rising and at the same time volatile energy prices on the investment decision. As a result, we demonstrate how a GDC investment contributes to a sustainable business strategy by reducing both energy consumption and exposure to rising energy prices.

The remainder of this paper is structured in the following manner. Section 2 provides an overview of existing literature as well as insight into the problem context. Section 3 describes the modeling approach, objective function, and optimal GDC investment budget. Section 4 presents the application of the proposed model based on exemplary and real-world data. Section 5 concludes the paper, offering perspectives relevant to further research.

2 Literature and Requirements

The progress in making data centers more environmentally friendly is part of a movement which demands that IS research and industry should take more responsibility for environmental issues (Watson et al., 2010). This association between IS and environmental issues is analyzed by Melville (2010), who concludes that IS is "an important but inadequately understood weapon in the arsenal of organizations in their quest for environmental sustainability" (p. 14). The technical possibilities of IS-enabled efficiencies are demonstrated in a widely recognized study published by The Climate Group (2008), who also conclude that the IS industry can play a key role in the transition to a low-carbon economy. Accordingly, IS-enabled energy efficiency programs can help to reduce emissions of up to 7.8 billion tons of carbon dioxide equivalent (CO2e) and lead to cost savings amounting to $946.5 billion by 2020. Similar results were reported in further studies and articles by Choi-Granade et al. (2009) and GeSI

(2013). Academic research has begun to examine how organizations develop and handle the possibilities offered by sustainable IS. For example, Molla et al. (2009) investigate organizational capabilities to engage in environmentally friendly IS. Chen et al. (2009) analyze the types of institutional pressure that influence the adoption of sustainable IS. They conclude that, apart from moral factors, pragmatic and financial concerns influence an organization's decision to adopt green technology. Also adopting a financial perspective, Schmidt et al. (2010) demonstrate the interplay of financial and environmental requirements, and Seidel et al. (2010) demand that organizations should consider ecological and economic objectives in a balanced way. Considering the organizational planning of sustainable IS investment projects, Hertel and Wiesent (2013) introduced a general approach for determining the optimal size of Green IS projects that considers both environmental and economic impacts.

According to vom Brocke and Seidel (2012), sustainable IS measures comprise a wide range of application, e.g. energy informatics (Watson et al., 2010), remote work via virtualization (Bose and Luo, 2011) or coordination of electric vehicles (Wagner et al., 2013). As a consequence, when planning sustainable IS projects, the different specifics of the regarded investment types (e.g. software, data centers, monitoring systems) have to be taken into consideration.

Accordingly, when analyzing the (direct and indirect) impacts of environmentally sustainable IS, specific concepts for decision-making are required (Bai and Sarkis, 2013). Even though data centers constitute a key field of application for sustainable IS, the specific impact of GDC has not yet been analyzed from an investment perspective.

2.1 Background

Global data centers are the fastest growing contributor to the information and communication technology (ICT) sector's carbon footprint due to the vast amount of data that is stored and instantly made available upon request (GeSI, 2013). The ongoing virtualization of business processes and the increase of cloud services such as infrastructure or applications delivered over the internet have further driven the demand for data center computing power (Armbrust et al., 2010). On the other hand, spiraling energy prices drive up operational costs of data centers and threaten to crowd out other innovation investments (Kaplan et al., 2008). As energy costs for data centers have more than quadrupled in the last ten years, data center energy consumption has become a board-level concern (BMU, 2008).

Simultaneously, multiple studies have identified measures which can be taken in existing data centers of all sizes and purposes, ranging from simple server rooms to data centers that host mission critical computer systems, to increase energy efficiency (BMU, 2008; dena, 2012; Kaplan et al., 2008). Accordingly, the optimization of data centers offers a significant potential to reduce energy consumption and increase *energy efficiency performance*. As energy is consumed in the data center's *ICT subsystem* (e.g. servers, storage, networking) and by its *infrastructure* (e.g. heating, ventilation, air-conditioning), both have the potential to boost efficiency (Jin et al., 2013).

Considering the *ICT subsystem*, optimization measures begin with analyzing the demand for applications and data as well as consolidation of servers. According to BMU (2008), usually about one third of applications operated on the servers are obsolete and can be deleted. As server utilization rarely exceeds 6% (Kaplan et al., 2008), efficiency can be further improved by virtualization of servers, which holds a potential to boost utilization up to 85% (BMU, 2008). At the same time, efficiency gains can be realized through energy-saving IT hardware, such as servers with high performance per watt or power-efficient storage. In case of short-term power outages, server availability is provided instantaneously by UPS systems. Due to the double conversion of alternating current of the grid to direct current of the battery back to alternating current of the IT hardware, energy losses around 10% are usual, but also avoidable through efficient and well-aligned UPS systems (dena, 2012).

Considering *infrastructure*, the optimization of air conditioning is a central point in improving energy efficiency. According to BMU (2008), the energy consumption used for cooling can be as expensive as

the energy used for operating IT hardware. According to various studies mentioned above, optimization measures include (among others) loss-free air circulation, separate hot and cold aisles, efficient cooling equipment and thermal management of air-conditioning based on utilization. Regarding these and other optimization measures, GDC planning requires a clear understanding of existing technologies and possibilities as well as a precise analysis of the potential measures.

This paper seeks to contribute to the ability of organizations to evaluate a comprehensive package of the opportunities presented above from an investment perspective. In doing so, we assume a company that has analyzed and identified possible measures in the field of both ICT subsystem and infrastructure that increase its data center's energy efficiency.

2.2   Quantitative valuation of Green Data Centers

When CIOs strive to engage in the greening of their data centers, they are confronted with two key questions, *What must we do?* and *How must we do it?* (Lubin and Esty, 2010). Answering the first question involves identifying potential for boosting energy efficiency by considering the technological possibilities mentioned above. For this paper, it is assumed that this question has already been answered by performing an analysis of the environmental potential as recommended by Kaplan et al. (2008). Answering the second question entails designing an investment project that is not only advantageous for the environment, but also economically profitable. Therefore, this paper focuses on the second question by determining an investment budget which maximizes the economic value added by the GDC investment project. In other words, the second question can be understood as *What is the optimal GDC investment budget that reconciles both environmental and economic objectives?* By deriving requirements from literature, we build a decision model that integrates the specifics of GDC into a framework for investment evaluation based on established decision theory.

GDC investments are associated with costs and benefits. Costs depend on the extent of the investment project. Benefits of the GDC investment consist of reduced energy costs for data center operation due to increased energy efficiency (*energy efficiency performance*). At this, efficiency measures in both the ICT subsystem and data center infrastructure are considered. However, real-world case studies have shown that GDC investments also involve an additional organizational impact besides energy efficiency performance (BMU, 2008). For instance, a GDC investment that is intended to increase energy efficiency in the ICT subsystem by implementing modern technology servers may also improve the overall data center performance, which constitutes value for the whole organization. The organizational value of IS in general has widely been discussed in IS literature (Brynjolfsson and Hitt, 1996; Kohli and Devaraj, 2003; Melville et al., 2004). Melville et al. (2004) define the business value of IS as "the organizational performance impacts of information technology at both the intermediate process level and the organization-wide level, and comprising both efficiency impacts and competitive impacts" (p. 287). Accordingly, we adopt a holistic definition for the benefits of GDC investments that comprises both *energy efficiency* and *organizational performance*. We postulate the following requirement:

R1: The valuation of GDC investments must consider costs and benefits (energy efficiency and organizational performance).

Besides lowered energy consumption, energy cost savings also depend on the future development of energy spot prices. Unless companies produce energy on their own, they usually act as price takers in the energy market, which means their energy consumption is not high enough to impact energy prices. Due to the discrepancy between finite non-renewable energy supply and seemingly infinite energy demand, it is assumed that energy prices will continue to rise (Lior, 2012). This development must be considered when evaluating future energy costs and savings. Furthermore, even though energy spot prices follow an increasing long-term trend, the short-term realization of energy prices is uncertain due to deviations from the deterministic trend (Geman, 2005). This fluctuation is largely caused by growing speculation on energy prices (Lior, 2012), as speculative short-term trading increases price volatility of energy sources (Duffie et al., 1999). When considering uncertain energy prices, we disclose that reduced

energy consumption results in reduced volatility of energy costs. Accordingly, the GDC investment decreases exposure to energy cost fluctuations and increases planning reliability. In order to demonstrate this remarkable effect, our valuation approach distinguishes between long-term trend and short-term volatility of energy prices:

R2: The valuation of GDC investments must separately consider a) the long-term development and b) the short-term volatility of energy prices.

As companies pursue economic objectives, their decision-making is focused on maximizing the utility of GDC investments, i.e. its value added according to decision theory (Bernoulli, 1954). Investment decisions are based on the ex-ante valuation of the investment project in question (Copeland et al., 2005). The value can be assessed by both qualitative and quantitative approaches (Verhoef, 2002).

In our paper, we focus on quantitative aspects in order to assure intersubjective comprehensibility and measurability in monetary terms. When determining the value of future costs and benefits, the cash flows of the GDC investment have to be discounted in order to reflect present value. Since one objective of this paper is to separately analyze the impact of volatile energy prices, we first adopt a valuation based on expected returns (i.e. expected energy price development) before integrating risk by considering uncertain, volatile energy prices. A combination of expected return and risk contribution, called risk-adjusted value, has already been suggested by Fridgen and Müller (2009) and Hertel and Wiesent (2013) in the context of IS decisions.

R3: The GDC investment decision has to be based on an objective function that determines the ex-ante value of the investment project with regard to expected returns and risks.

3 Optimizing Green Data Center Investment Budgeting

So far, to the best of our knowledge, there are no valuation methods for investment decisions in GDC that fulfil the imposed requirements. The decision model presented here is designed to take into account the technological possibilities and measures presented above from a comprehensive point of view. Its aim is to determine the ex-ante optimal investment budget which maximizes the value added by the GDC project. This value is determined according to the *with and without principle*, which means that it is evaluated by comparing the situation *before* and *after* the investment project. The result of this delta analysis is the *net present value* (*NPV*) when considering the expected energy price development, respectively *risk-adjusted net present value* (*raNPV*) when considering volatile energy prices.

3.1 Research methodology

In order to analyze the impact of GDC investments, we use the research approach introduced by Meredith et al. (1989) which structures research activities in a continuous, repetitive cycle of description, explanation and testing. Accordingly, this iterative process enables us to describe and explain an observable economic fact in a structured manner. At first, we (formally) describe certain cause-and-effect relationships that affect the evaluation of GDC investments (e.g. influence of volatile energy prices on the GDC investment value). As new findings cannot always be derived from practical observations, we use a formal deductive modeling approach. Subsequently, we explain the achieved findings and try to generate (practical) recommendations.

The testing of the findings revealed with this approach shall be subject to future empirical research. However, as a starting point for the empirical validation and to illustrate the utility of our decision model, we will demonstrate a practical application based on exemplary project data and real-world energy prices.

3.2   Setting and assumptions

At first, the GDC investment's *NPV* is determined by formalizing the relationship between the investment budget I_0 and the investment's returns within time frame *T*. Subsequently, the risk that originates from fluctuating energy prices is integrated into our evaluation in order to determine the GDC investment's *raNPV*. Based on this, the optimal GDC investment budget I_0^* can be identified. Finally, we analyze the effect of volatile energy prices by comparing the optimal investment budget with and without consideration of volatile energy prices. We set the following assumptions:

A1: The GDC investment is infinitely divisible[2] and characterized by its budget $I_0 \geq 0$.
A2: The present value is determined by discounting periodic cash flows by a risk-free rate of return i.

Referring to R1 (consideration of costs and benefits): Costs and benefits are measured in terms of money. Costs of I_0 arise when the GDC investment is implemented in *t=0*. Depending on the size of the investment budget I_0, periodic benefits, i.e. returns, increase. Returns are regarded for each period of the data center's operation ($t \in \{1,...,T\}$) and determined considering periodic energy cost savings $\Delta EC_t(I_0)$ (energy efficiency performance) and further organizational value induced by the investment $OV_t(I_0)$ (organizational performance). As mentioned, energy cost savings $\Delta EC_t(I_0)$ depend on reduced energy consumption and the energy price's development. Regarding the former, we assume that the GDC investment permanently reduces periodic energy consumption (measured in megawatt hours [MWh]) by $\Delta E(I_0) = E_{old} - E_{new}$. In order to economically value the reduction of energy consumption, $\Delta E(I_0)$ must be multiplied by the future expected energy spot price P_t per MWh. We further assume that both reduction of energy consumption $\Delta E(I_0)$ and further organizational value $OV(I_0)$ are constant in each period, so we can disregard the time indices *t*.

Referring to R2a (consideration of long-term development of energy prices): The future development of energy prices is determined by referring to the periodic price P_t, which is predicted for each period *t*. The long-term increasing trend is modeled as a deterministic function of time (Geman, 2005). This trend comprises any regularities and genuine periodic behavior of the energy spot price and reflects its expected long-term development over time.

A3: Energy prices P_t follow an increasing linear trend over the long run, $P_t = P_0 + a \cdot t$, $P_0 > 0$, $a > 0$

The deterministic price trend is formalized with a periodical price increase, indicated by parameter *a*. The temporal development of energy prices is implied by parameter *t*. By assembling the introduced components, the GDC investment's NPV can be assessed as follows:

$$(1) \qquad NPV(I_0) = -I_0 + \Delta E(I_0) \cdot \sum_{t=1}^{T} \frac{P_0 + a \cdot t}{(1+i)^t} + OV(I_0) \cdot \sum_{t=1}^{T} \frac{1}{(1+i)^t}$$

This valuation assumes a constant development of energy prices and disregards the risk of fluctuating energy prices. In the following, we extend our approach by considering volatile energy prices and their effects on the valuation of the GDC investment decision. When introducing uncertain energy prices $\tilde{P}_t$, we have to consider that energy costs prior to the GDC investment have already been exposed to fluctuation. By enabling energy efficiency, the GDC investment reduces energy consumption, and therefore also reduces exposure to energy cost fluctuation. As mentioned above, we want to quantify this effect and examine its impact on the optimal investment budget.

Referring to R2b (consideration of short-term fluctuation of energy prices): Even though energy prices follow an increasing long-term trend, the short-term realization of energy prices is uncertain due to deviations from the deterministic trend (Geman, 2005). Taking this into account, future stochastic

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[2] For matters of modeling and without loss of generality, we abstain from a more realistic discrete range of project sizes.

energy prices are exposed to variations within a certain point of time. For the sake of simplicity, we set the following assumption:

A4: Short-term stochastic energy price fluctuations $\tilde{X}_t$ are independent and identically distributed.

This assumption is represented by the stochastic process $(\tilde{X}_t)_{t=0}^{T}$ with $\tilde{X}_t \sim N(0, \sigma_X)$. Following the work of Lucia and Schwartz (2002) and Geman (2005), the uncertain energy spot price $\tilde{P}_t$ can be modeled as a discrete arithmetic Brownian motion. For the sake of simplicity, we employ the following approach with consists of two components: First, the deterministic price trend $(a \cdot \Delta t)$ reflects the expected long-term development over time as described above. Second, the stochastic component $\left(\Delta \tilde{X}_t = \tilde{X}_{t+\Delta t} - \tilde{X}_t\right)$ describes deviations from the deterministic trend.

$$(2) \qquad \Delta \tilde{P}_t = \tilde{P}_{t+\Delta t} - \tilde{P}_t = \left(P_0 + a \cdot (t + \Delta t) + \tilde{X}_{t+\Delta t}\right) - (P_0 + a \cdot t + \tilde{X}_t) = a \cdot \Delta t + \Delta \tilde{X}_t$$

We use the energy price's periodic standard deviation $\sigma(\tilde{P}_t) = \sigma(\tilde{X}_t)$ to quantify the fluctuation of energy prices. Fluctuating energy prices lead to fluctuating energy costs. As this model implements a delta analysis of the situation before and after the GDC investment, we quantify the reduced exposure to fluctuating energy costs by applying the rules of linear transformation of random variables. This means that even though the deviation of energy prices remains constant, the absolute deviation of the company's energy costs is reduced due to decreased energy consumption by

$$(3) \qquad -\sigma\left([E_{old} - E_{new}] \cdot \tilde{P}_t\right) = -\sigma\left(\Delta E(I_0) \cdot \tilde{P}_t\right) = -\Delta E(I_0) \cdot \sigma(\tilde{X}_t)$$

The negative sign indicates the risk mitigating effect of the GDC investment, which means deviation of energy costs is actually decreased. For our valuation, the total decrease of deviation within T can be formalized by a risk component $\widetilde{RC}_T$, which is determined by applying the general equation for calculating standard deviations.[3] As energy price fluctuations $\tilde{X}_t$ are stochastically independent, $\sigma(\tilde{X}_t)$ can be summed up for all time periods t without taking into account the correlations ρ_{ij}.

$$(4) \qquad RC_T(I_0) = -\sqrt{\sum_{t=1}^{T} \frac{\sigma_t^2(\Delta E(I_0) \cdot \tilde{P}_t)}{(1+i)^t}} = -\Delta E(I_0) \cdot \sqrt{\sum_{t=1}^{T} \frac{\sigma_t^2(\tilde{X}_t)}{(1+i)^t}}$$

Referring to R3 (determination of the ex-ante value with regard to expected returns and risks.): The objective of this paper is to determine the optimal GDC investment budget on the basis of risk and return. Therefore, we draw on the decision theory (Bernoulli, 1954) and include the decision-maker's risk aversion. In order to integrate risk and return into one decision calculus, we define that the *raNPV* of the GDC investment corresponds to the following preference function, with μ representing the GDC investment's expected *NPV* and σ the *NPV*'s standard deviation. Individual risk aversion is defined by a constant parameter $\alpha \geq 0$ (Pratt, 1964).

$$(5) \qquad \phi(\mu, \sigma) = \mu - \alpha \cdot \sigma$$

Accordingly, risk-neutral decision-makers ($\alpha = 0$) base their decisions solely upon the expected *NPV*, whereas risk-averse decision-makers ($\alpha > 0$) allow for risks by subtracting the risk-premium $\alpha \cdot \sigma$. In decision theory, risk-aversion is usually assumed (Bamberg and Spremann, 1981).

As this paper focuses on energy efficiency performance induced by GDC investments, the *NPV*'s standard deviation is limited to the effects of volatile energy spot prices. Thus, risk is only considered in terms of volatile energy prices, as formalized in the risk component $\widetilde{RC}_T$. Other causes that lead to

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[3] $\sigma_n = \sqrt{\sum_{i=1}^{n} \sigma_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} \rho_{ij} \sigma_i \sigma_j}$

fluctuations of the *NPV* (e.g. deviating costs of implementation) are not taken into account. In considering these deliberations, we define the objective function $raNPV$ by inserting NPV (1) and $\widetilde{RC}_T$ (4) into the preference function $\phi(\mu, \sigma)$:

$$(6) \quad raNPV(I_0) = -I_0 + \Delta E(I_0) \cdot \sum_{t=1}^{T} \frac{P_0 + a \cdot t}{(1 + i)^t} + OV(I_0) \cdot \sum_{t=1}^{T} \frac{1}{(1 + i)^t} - \alpha \left(-\Delta E(I_0) \cdot \sqrt{\sum_{t=1}^{T} \frac{\sigma_t^2(\tilde{X}_t)}{(1 + i)^t}} \right)$$

3.3 Identifying the optimal GDC investment budget

A decision-maker can apply this objective function to identify the optimal GDC investment budget with regard to costs, returns and under consideration of volatile energy prices. To address this issue, the *raNPV* of the GDC investment has to be maximized, with I_0 representing the independent variable. To analytically solve this optimization problem, the course of the functions *ΔE(I₀)* and *OV(I₀)* has to be analyzed and described. In the following, we propose formalizations of these functions that are deliberately generically designed in order to illustrate fundamental relationships of the GDC investment. By adapting these formalizations, our decision model can always be adjusted to more particular GDC investment projects.

In general, we hold that returns, i.e. energy efficiency *ΔE(I₀)* and further organizational value *OVt(I₀)*, increase in accordance with the investment project's size, which is characterized by the employed investment budget I_0. However, we have to take into account that the positive impact of the investment is usually characterized by diminishing marginal utility. This relation has been established by Verhoef (2002) for general IS projects, and studies regarding GDC investments have substantiated this finding (BMU, 2008; dena, 2012). One possibility for formalizing the relationship between energy efficiency performance, or, more precisely, reduced energy consumption, and the investment budget is $\Delta E(I_0) = e \cdot I_0^{\beta}$. The factor *e* corresponds to the permanent reduction of energy consumption when the investment amount is increased by one monetary unit. Accordingly, *e* is measured in saved energy consumption per monetary unit and indicates the efficiency performance of the GDC investment. We also assume that *e > 0*, because otherwise the investment project wouldn't have any effect on the data center's energy efficiency, and therefore we wouldn't consider it as GDC investment. The exponent $\beta \in]0; 1[$ represents the diminishing marginal utility of the investment. If energy consumption is reduced almost constantly when the GDC investment budget I_0 is increased, β is close to 1.[4] Accordingly, $\Delta E(I_0)$ is described as a strictly monotonically increasing $(\delta \Delta E(I_0)/\delta I_0 > 0)$ and strictly concave $(\delta^2 \Delta E(I_0)/\delta I_0^2 < 0)$ function.

For the sake of simplicity, we propose a formalization of the relation between organizational performance and the investment budget according to the previous pattern, so $OV(I_0) = v \cdot I_0^{\beta}$. Here, the factor *v ≥ 0* represents the additional monetary value created when the investment amount is increased by one monetary unit. If the GDC investment does not affect the company's organizational performance at all, then *v = 0*. Furthermore, we assume that the diminishing marginal utility, which is indicated by *β*, affects both energy efficiency and organizational performance in the same way. Summarized, $OV(I_0)$ can also be described as a strictly monotonically increasing $(\delta OV(I_0)/\delta I_0 > 0)$ and strictly concave $(\delta^2 OV(I_0)/\delta I_0^2 < 0)$ function. On this basis, we can formalize the objective function *raNPV* as follows:

$$(7) \quad raNPV(I_0) = -I_0 + e \cdot I_0^{\beta} \cdot \sum_{t=1}^{T} \frac{P_0 + a \cdot t}{(1 + i)^t} + v \cdot I_0^{\beta} \cdot \sum_{t=1}^{T} \frac{1}{(1 + i)^t} - \alpha \left(-\left(e \cdot I_0^{\beta}\right) \cdot \sqrt{\sum_{t=1}^{T} \frac{\sigma_t^2(\tilde{X}_t)}{(1 + i)^t}} \right)$$

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[4] We exclude *β = 1*, as this would indicate an unrealistic linear increase of the (*ra)NPV* when extending the project size *I₀*.

A mathematical analysis shows that a higher investment budget (first summand) is economically reasonable as long as it is compensated for by increased energy efficiency (second summand) and organizational performance (third summand) as well as by decreased energy cost deviation (fourth summand). The analytical determination of the optimal investment budget $I_0{}^*$ requires the maximization of the *raNPV* induced by the GDC investment ($\delta raNPV(I_0)/\delta I_0 = 0$ and $\delta^2 raNPV(I_0)/\delta I_0{}^2 < 0$). As a result, we maintain the following optimal investment budget $I_0{}^*$:

$$(8) \qquad I_0^* = \left(\beta \cdot e \cdot \sum_{t=1}^{T} \frac{P_0 + a \cdot t}{(1+i)^t} + \beta \cdot v \cdot \sum_{t=1}^{T} \frac{1}{(1+i)^t} + \alpha \cdot \beta \cdot e \cdot \sqrt{\sum_{t=1}^{T} \frac{\sigma_t^2(\tilde{X}_t)}{(1+i)^t}} \right)^{1-\beta}$$

Overall, the opposing effects constitute a trade-off that leads to the existence of an optimal investment budget $I_0{}^*$. In this case, the GDC investment promotes environmentally sustainable development that is consistent with the economic requirements of the company. In general, the GDC investment project should be conducted if the *raNPV* that results from investing a budget I_0 is positive. Furthermore, a decision-maker should raise the GDC investment budget up to $I_0{}^*$. When investing less than $I_0{}^*$, an increase of the investment volume leads to higher risk-adjusted returns compared with the necessary payouts. When investing more than $I_0{}^*$, the additional payouts exceed the additional benefits of the GDC investment.

From a strictly environmental perspective, intensification beyond $I_0{}^*$ might be desirable for maximizing environmental sustainability. However, in order to promote environmental sustainability as well as guarantee the long-term existence of economic entities, the coherence of both economic and environmental objectives has to be considered.

3.4 Analyzing the effect of volatile energy prices

Finally, we analyze the effect of volatile energy prices on the optimal investment budget. Therefore, we draw on the *NPV* as defined above (see 1) in order to determine the optimal investment budget when disregarding volatile energy prices. This optimal budget I_0' serves as a benchmark in our analysis. When optimizing the GDC investment's *NPV*, we get the following result:

$$(9) \qquad I_0' = \left(\beta \cdot e \cdot \sum_{t=1}^{T} \frac{P_0 + a \cdot t}{(1+i)^t} + \beta \cdot v \cdot \sum_{t=1}^{T} \frac{1}{(1+i)^t} \right)^{1-\beta}$$

When comparing the optimal results with and without consideration of volatile energy prices, we obtain the, at first sight, counterintuitive result that $I_0^* \geq I_0'$ for $\alpha > 0$.[5] Accordingly, the maximum *raNPV* exceeds the maximum *NPV*. This can be explained by the fact that integrating uncertainty reveals reduced exposure to volatile energy prices, which increases the value of the GDC investment. From a decision-maker's viewpoint, this means that the GDC investment not only enhances energy efficiency and organizational performance, but it also reduces dependence on volatile energy markets by the factor $\alpha \cdot \widetilde{RC}_T$.

From a theoretical point of view, the consideration of fluctuating energy costs results in a higher maximum value of the GDC investment and in a relatively larger investment. From a business perspective, the costs of a GDC investment can therefore be compared with an insurance premium that is paid in order to limit future risks. That means the company can reduce dependence on volatile energy markets by paying an insurance premium in the form of investment expenditures in GDC. Therefore,

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[5] This is apparent when comparing I_0^* and I_0': The difference between the two originates from $\widetilde{RC}_T$, which is only considered in the objective function of I_0^*. Since $\widetilde{RC}_T \geq 0$ for all possible values and $\alpha > 0$, $I_0^* \geq I_0'$ holds.

our findings strongly suggest that decision-makers should consider this "insurance cover" against unforeseen energy price shocks granted by GDC investments in their investment planning.

We conclude our modeling approach by recapitulating the building blocks of our framework and their direct impact on the *raNPV* in Table 1.

	Costs	**Energy efficiency performance**	**Organizational Performance**	**Risk mitigating effect**
Formalization	$-I_0$	$e \cdot I_0{}^\beta \cdot \sum_{t=1}^{T} \frac{P_0 + a \cdot t}{(1+i)^t}$	$v \cdot I_0{}^\beta \cdot \sum_{t=1}^{T} \frac{1}{(1+i)^t}$	$-\alpha \left(-\left(e \cdot I_0{}^\beta \right) \cdot \sqrt{\sum_{t=1}^{T} \frac{\sigma_t^2(\tilde{X}_t)}{(1+i)^t}} \right)$
Impact on raNPV	negative	positive	positive	positive

Table 1. Summary of the modeling approach

4 Exemplary Application

We demonstrate the applicability of our decision model on the basis of exemplary data considering the GDC investment project and actual energy price data. In order to ensure maximum general validity, we derive data that represent a fictitious yet typical medium-sized company.

The data of the GDC project as well as its scaling is based on dena (2010). The company under consideration has identified energy cost savings potential through modernizing its data center's ICT hardware and infrastructure. An in-depth study has revealed a package of measures that increase energy efficiency while also improving the data center's original performance from an organizational perspective. Below, we present the analyzed data necessary to evaluate the data center modernization project. On this basis, the optimal investment budget which should be allocated to this project can be identified.

The ranges of the possible measures include optimizing air circulation and cooling, upgrading UPS systems, installation of virtual equipment and energy efficient IT hardware. According to the potential analysis conducted, energy efficiency performance of these measures correspond to *e = 5.0 kWh/€* and organizational performance is estimated as *v = 1.2·10⁻³ [€/€]*. Besides, due to the different impacts of the identified measures, efficiency gains are characterized by a diminishing marginal utility of *β = 0.9*. The considered time frame of the GDC investment project is 84 months (7 years), beginning in January 2014 (*t = 0*). The present value of the project is calculated for all *t ∈ {0,...,84}* by a monthly risk-free rate of return *i = 0.42%*, which corresponds to an annual rate of *5%*.

In order to estimate future expected energy prices and future volatility of energy prices, the stochastic energy price process must be determined. Therefore, we use an actual time series of monthly energy prices (in €/MWh) from January 2000 to October 2013 provided by the Federal Statistical Office of Germany (2013) as illustrated in Figure 1. This monthly time series is used for a linear regression to estimate the necessary parameters of $\Delta \tilde{P}_t = a \cdot \Delta t + \Delta \tilde{X}_t$ with $\tilde{X}_t \sim N(0, \sigma_X)$. Accordingly, the deterministic drift component a for the long-term expected price trend $a \cdot \Delta t$ is estimated as $a = 0.367$, and the standard deviation σ_X of the periodic energy prices $\Delta \tilde{X}_t$ equals $\sigma_X = 3.31 \ €/MWh$. The applied parameter values are shown in Table 2.

The estimated price trend *a* along with the initial energy price *P₀ = 117.34 €/MWh* for January 2014 (time of the GDC investment) is used to predict the expected energy spot prices $E(\tilde{P}_t)$ for the following 84 months. The periodic standard deviation σ_X of the future fluctuating energy prices is used to calculate

the decrease of energy cost fluctuation RC_T by discounting the periodic energy cost reductions and subsequently adding up the periodic values according to (4).

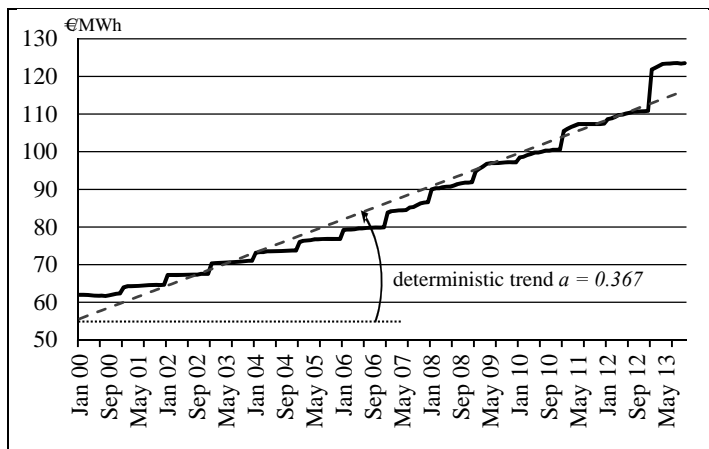| Parameter	Value
Energy efficiency performance e	5.0 kWh/€
Organizational performance v	$1.2 \cdot 10^{-3}$
Marginal utility β	0.9
Deterministic price trend a	0.367
Standard deviation of drift component σ_x	3.31 €MWh
Energy price P_0	117.34 €MWh
Risk aversion α	4
Discount rate i	0.42% p.m.
Time frame T	84 months

Table 2. Parameters of the project

Figure 1. Time series analysis of energy prices (in €/MWh)

Figure 2 illustrates the course of the GDC investment's *NPV* and *raNPV*, depending on the employed investment budget I_0. Both *NPV* and *raNPV* strictly increase until the increasing costs associated with the investment exceed the diminishing marginal impact of energy efficiency and organizational performance and, regarding the *raNPV*, the diminishing marginal impact of the risk component.
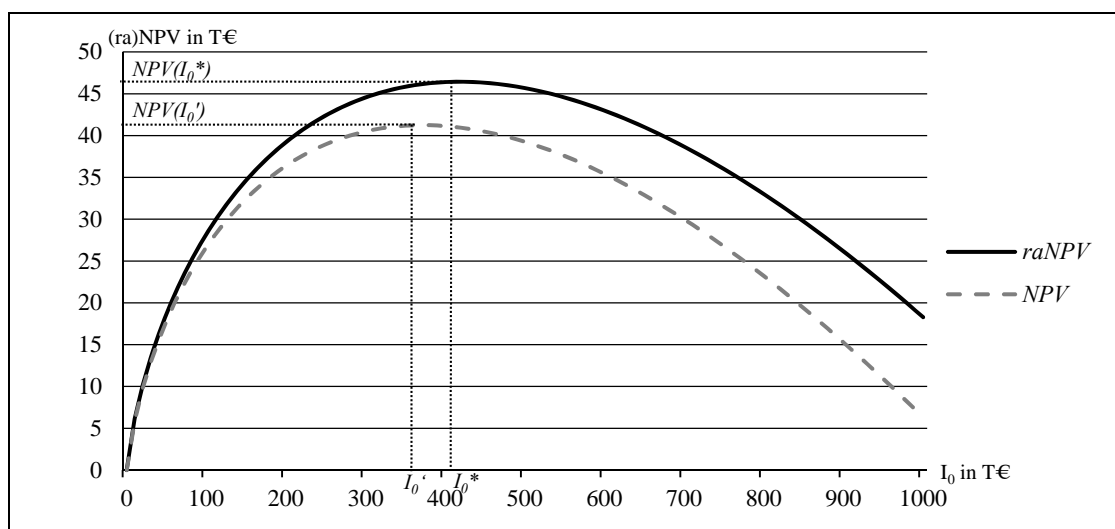

Figure 2. (Risk-adjusted) net present value of the GDC investment project

The optimal GDC investment budget of $I_0^*=417,900\ €$ corresponds to a maximum *raNPV* of *46,433 €*. In comparison, when disregarding fluctuating energy prices and evaluating the GDC investment solely according to the *NPV* (benchmark), the maximum *NPV* is reached at *41,251 €* for $I_0'=371,263\ €$. Accordingly, the company under-invests in GDC innovations by *46,637 €* if it disregards volatile energy prices.

These results support our findings in chapter 3.4, which indicate that energy efficiency measures save energy costs, increase overall (environmental and organizational) performance and generate an insurance effect. Our decision model helps to evaluate this effect and it obviates structural under-investments by considering energy price volatility. Besides, reduced exposure to volatile energy prices also decreases dependence on energy supply markets, which increases corporate independence. As

mentioned above, from an exclusively environmental viewpoint, it may seem unusual to limit investments to the economic rationale, as represented by the maximum *raNPV*. However, as efficiency continues to be increased by ongoing technical progress, this economic rationale also demands that tomorrow's advanced technology should be applied to promote environmental sustainability, which results in a long-term rational use of capital.

As in most quantitative models, this evaluation depends on the quality of the information used. To allow for a well-founded decision and to unlock the full potential of GDC, decision-makers must analyze the efficiency potentials offered by GDC opportunities carefully and with regard to technological innovations. Otherwise, both economically profitable and environmentally beneficial opportunities are missed out.

5　Practical Implications, Limitations and Outlook

The sustainable use of energy sources remains a key challenge for our and future generations. Due to non-renewable energy sources and rising energy prices, organizations have to increasingly realize the potential of energy efficiency as a source of environmentally friendly low-cost energy. Technological progress in the field of IS has created opportunities for improvements in energy efficiency. Empirical studies have confirmed the impact of innovative, sustainable IS on data centers. In this paper we contribute to this research. First, we present a decision model that optimizes the GDC investment budget with regard to its positive effect on a company's level of energy efficiency. Then, we use exemplary data of a GDC investment project in combination with an actual energy price time series to examine the decision model's influence on fluctuating energy prices and to demonstrate the positive effects of GDC investments. We are able to identify an investment budget that is compatible with both economic and environmental objectives. Furthermore, we demonstrate the structural decision error in the form of under-investments when disregarding volatile energy prices.

Our results show that GDC investments in energy efficiency reduce a company's dependence on volatile energy prices and therefore limit its exposure to fluctuations in the energy market. This risk-mitigating effect is crucial, as it increases the value of the GDC investment. From a theoretical point of view, we show that the consideration of fluctuating energy costs results in a higher maximum value of the investment and in a relatively larger investment. From a business perspective, the costs of GDC investments can be compared with an insurance premium that is paid in order to limit future risks. To avoid structural under-investment, we therefore suggest to consider the costs of GDC investments as insurance cover against fluctuations in the energy market. Similar results were obtained by Choi-Granade et al. (2009), who also reach the conclusion that investments in energy efficiency may improve the risk position of a company.

Nevertheless, the results and practical implications of our paper are restricted by some limitations, which can be seen as potential areas for further research. First, we had to limit ourselves to a certain type of risk (fluctuating energy prices). We understand that this approach ignores other common sources of risk as outlined by Wallace and Keil (2004). However, as we focus on energy-efficiency, this restriction does not interfere with our main results. Furthermore, for easier modeling, we assume the infinite divisibility of GDC investment projects, whereas finite divisibility would be more realistic. The simple energy price process, which contains independent short-term price fluctuations instead of the more commonly observed dependent fluctuations, could also be enhanced. Finally, we use exemplary data considering the GDC investment project in our application example in order to demonstrate the basic functionality of the model, i.e. to derive the optimal investment budget. For evaluating our model under even more realistic conditions, it would be beneficial to employ empirical GDC data in future research.

Our paper implies that organizations should acknowledge the impact of IS on energy efficiency for economic reasons and promote the implementation of GDC innovations as well as engage in the exploration of new technologies (Bai and Sarkis, 2013). Due to the rapid development of IS in the field

of energy efficiency, organizations can tackle sustainability in a profitable manner. However, we do not suggest that sustainability can only be achieved on the grounds of economic benefit and self-interest. Sustainable solutions are the result of a complex decision-making process that is strongly influenced by our social nature, non-economic priorities and behavior (Watson et al., 2012). In this paper, we have confined ourselves to an organizational perspective, neglecting human and social influences. These additional areas are covered in ongoing research. Due to the relevance to global climate change and corporate responsibility, sustainable IS will remain at the heart of future IS research (Brooks et al., 2012). However, it is evident that tackling the challenges of sustainability requires not only the concerted effort of IS academics, scholars, and practitioners, but interdisciplinary cooperation between professionals in the fields of science, politics, industry, and society.

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