CONTRIBUTION OF ICT TO AN INTELLEGENT ENERGY SYSTEM – A CASE STUDY ON PREDICTIVE MAINTENANCE OF POWER TRANSFORMERS

Christopher Koch, Department of Energy Systems - TU Berlin, +49 (0)30 314 28634, christopher.koch@tu-berlin.de
Simon Letzgus, Department of Energy Systems - TU Berlin, +49 (0)30 314 28634, simon.letzgus@tu-berlin.de

1. Overview

Decarbonization of the electricity sector leads to increasing deployment of renewable, non-dispatchable and distributed generation units in energy systems around the world. The consequent increase in system complexity makes system operation and organization more demanding. At the same time advances in information and communication technology (ICT), meaning hardware and software for data processing, transmission and storage, provide sophisticated tools for real-time communication between stakeholders and infrastructure. This helps to monitor and control system states enabling more effective and coordinated actions to optimize operation even in highly complex electricity systems.

Several studies address the general potential of digitization along the energy-economical value chain (A.T. Kearney et al. 2018; Vogel et al. 2019; PWC 2018). But only little research focuses on the contribution of ICT to a more efficient energy system including qualitative and quantitative evaluation of its system-wide impact. This paper addresses this research gap by introducing a method which enables the evaluation of ICT contributions to specific energy system related challenges. The goal is to quantify the impact of ICT-based optimization regarding the multi-dimensional objective function targeting competitiveness, security of supply and environmental sustainability. The question we aim to answer is whether ICT enables convergence towards a pareto-optimal solution. This requires an improvement of at least one of the three dimensions without impairing another one.

The remainder of the paper is organized as follows: In section 2 the methodological approach is introduced. It suggests a series of expert interviews followed by deduction and evaluation of criteria for the multi-dimensional objective. Then the method is applied to a case study on predictive maintenance of power transformers. First, the findings from an expert interview are presented including potentials and challenges of ICT for the specific task. The results are then combined with an in-depth literature study for evaluating the consequences of ICT-driven predictive maintenance of power transformers in the different dimensions of the objective function. Lastly, the findings are projected to a system level with quantitative results for competitiveness, environmental sustainability and security of supply. It is shown that ICT-driven predictive maintenance of power transformers indeed holds the potential to achieve a better pareto-optimal system state with potential improvements in all analyzed dimensions.

2. Method & Background

In recent years parts of the value chain, technologies or applications have been labelled to be “intelligent” or “smart”, also in the energy domain. The well-established term “smart grid” might be the most prominent example. Although difficult to formalize, the application of ICT stands at the core of the concept of intelligent energy systems. In this contribution, ICT means hardware and software for data processing, transmission and storage. It therefore includes sensors, communication infrastructure but also optimization algorithms. Due to the nature of this paper this rather general definition is applied to ICT solutions applied in the energy domain. However, intelligent energy systems do not use ICT as an end in itself. Usually the application is clearly linked to the optimization of a specific task. In the smart grid example this would be to keep a relatively small system that is difficult to control in balance. The methodology suggested in this paper incorporates this observation by evaluating the ICT impact on a certain focus area, in this paper called energy system specific challenge. Potential examples are forecasting renewable production or the development of new flexibility potentials. Such challenges can be chosen from both a system and an asset level.

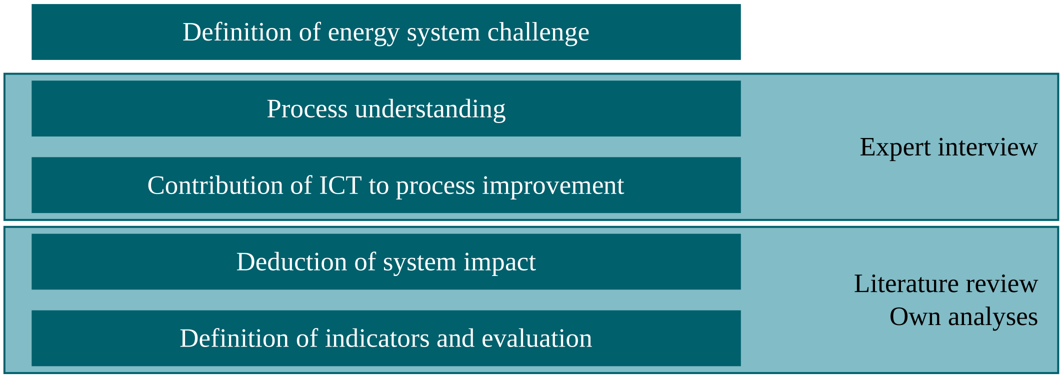

Figure 1: Methodology to assess the impact of ICT within a specific energy system challenge.

Figure 1 describes the methodology to assess the impact of ICT for a specific energy system challenge starting out from the definition of the challenge which is to be assessed. The second step is to gain a detailed understanding of the underlying processes by means of expert interviews. Here, it is important to follow the same consistent guideline for every interview to ensure the comparability of the collected information (Mieg and Näf 2006). At this stage, the main objective is to unveil the qualitative contribution of ICT to the process. To prepare the interview, a process diagram is developed to formulate hypotheses regarding ICT-based optimization potential and ICT-related challenges for each process step. Figure 2 shows an exemplary general process diagram for ICT-contribution to a specific challenge. It must be specified and adjusted to fit the respective challenge at hand. The formulated assumptions are then discussed with the expert to gain comprehensive insights in the required level of detail.

Figure 2: General process steps in system optimization with high ICT potential.

The interview insights are the base for evaluating the potential contribution of ICT to the specific challenge. However, a crucial point is still missing: The essential question against what objective the ICT contribution should be evaluated. When assessing system-wide impact we argue that all three dimensions of the energy policy triangle must be addressed. Therefore, the initial, still qualitative evaluation projects the ICT process-contribution onto the three energy policy goals competitiveness, security of supply and sustainability (compare Figure 3). This is followed by a definition of indicators to quantify the effects. The evaluation can either be done with the help of appropriate studies or by carrying out own analyses. For the specific case of predictive maintenance for power transformers, we base our own analysis and calculations on studies about economic aspects (Siemens 2014; Westman et al. 2010) and potential ecological impacts of power transformers (ABB 2003a, 2003b; Jorge et al. 2012).

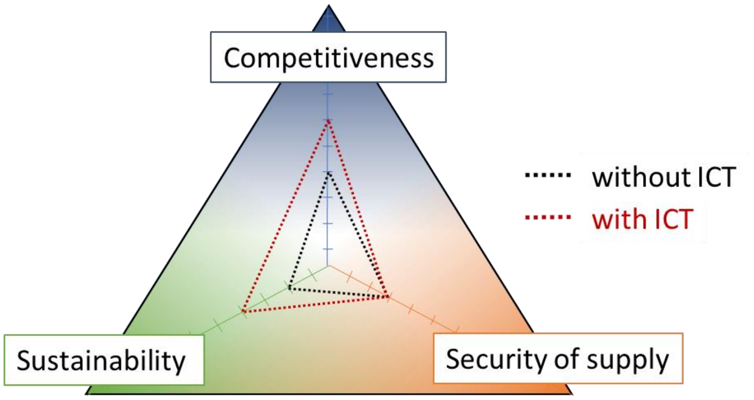

Figure 3: Projection of ICT-contribution onto the three dimensions of the energy policy triangle.

3. Results of expert interview

We apply the presented method to evaluate ICT contribution on intelligent maintenance and investment planning of energy infrastructure. In particular, we focus on the application of predictive maintenance to power transformers. Maintenance strategies can be divided into being reactive or proactive (Azadeh and Abdolhossein Zadeh (2015), compare Figure 4). Reactive or corrective maintenance reflects a policy to repair or replace a component after a failure has occurred. This strategy is generally not applied to high voltage power transformers because of the high replacement costs and long delivery times of new assets. Currently, it is common practice to follow a preventive maintenance strategy with constant intervals between on-site inspections which is four years according to DIN VDE 0105-100. Predictive maintenance on the other hand aims to determine the optimal service interval for each transformer individually based on its current and predicted future condition. The following analysis focuses on high-voltage transformers (110 kV to 10, 20 or 30 kV).

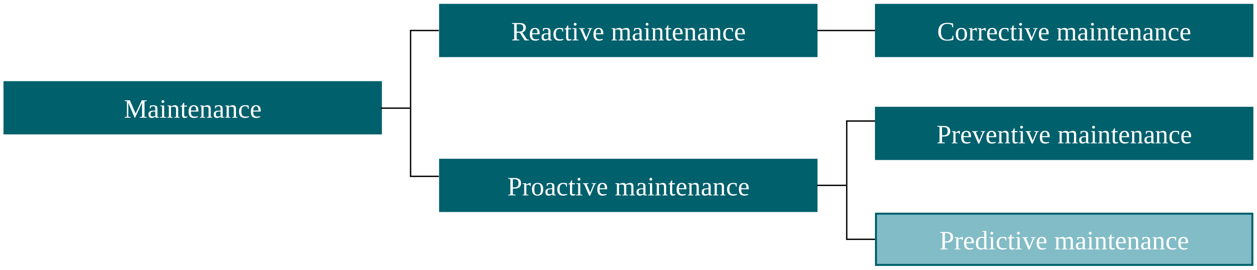

Figure 4: Maintenance strategies for technical assets. Illustration based on Azadeh and Abdolhossein Zadeh (2015).

In preparation to the conducted expert interview (Koch, Letzgus (11/16/2018) the process chart displayed in Figure 5 was created. The individual steps were then discussed with the expert to gain detailed knowledge about the underlying process and to identify the potential ICT contribution to each of them. It was confirmed that all steps expose high ICT penetration. They will be discussed in greater detail in the following sections.

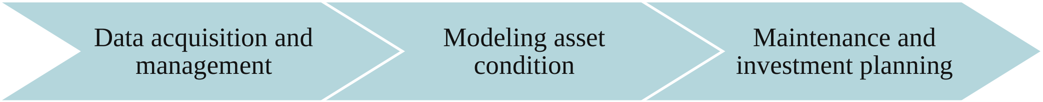

Figure 5: Diagram of the process for maintenance and investment planning of power transformers.

3.1. Data acquisition and management

Predictive maintenance needs a consistent data set including asset data, grid operation data and maintenance information. The necessary information usually must be collected from two different data sources. The data warehouse contains information on the equipment (e.g. manufacturer and year of construction) which are usually collected for company’s purposes (Devlin 2000). There is also information on maintenance reports including dissolved gas analyses. Those are necessary to estimate the technical and electrical status of the transformer by investigating critical factors such as the thermal decomposition of cellulose insulation and arcing must be estimated indirectly via dissolved gas analyses (Gill 2009; Imani et al. 2018). Normally, data analysts can get direct access to this information. This is not possible for the data on grid and transformer load stemming from the control system. These critical data must be mirrored for security reasons. Additionally, these data are stored in a high time resolution, which requires an aggregation to an appropriate period.

Heterogeneous data are also the biggest challenge of this process step. It is burdensome to generate a consistent data set from the different databases and it needs collaboration of different stakeholders and concatenation of different data sources and types. Furthermore, data bases must occasionally be migrated to use more efficient database structures for handling the huge amount of data from longstanding measurements. Another challenge is to transfer manual data to a digital format. The benefit of such measures must be checked individually, but it is difficult to estimate the costs of collecting the data and the improvement of the optimization model. However, the digitization of maintenance is normally beneficial as the data are crucial for predicting future asset status (Koch, Letzgus 11/16/2018). An efficient way is to utilize tablet computers which can be also used for real-time communication of updated routes to the maintenance staff (see section 3.3).

3.2. Modeling asset condition

The collected data are used to analyze and predict the actual and future status of a power transformer. This step often involves advanced data analysis and modelling. The goal is to anticipate whether a transformer will require maintenance actions during the upcoming period. Predictive maintenance shall prevent unnecessary on-site maintenances and enable a lifetime extension due to early detections of possible damages. This needs a binary classification model (Alpaydin 2010) forecasting the probability of the occurrence of a critical condition including the current system status and the estimated future stress.

The optimization problem must consider the significant difference in costs between a false positive and a false negative prediction (Koch, Letzgus 11/16/2018). If the model classifies a transformer to be critical even though it is stable, it costs only an additional dissolved gas analysis. If the model does not detect a critical asset, it may lead to a total loss and the transformer must be replaced. So, the objective function must include the expected costs of each case to optimize the total costs, and not the accuracy.

Increasing the forecast quality requires an iterative process with feedback loops between data analysts and engineers. Such a time intensive approach is only beneficial for large grid operators with many assets. Scalability of predictive maintenance can be improved if methods and model configuration are transferable from one grid area to another.

3.3. Maintenance and investment planning

The condition-model results are used for maintenance and investment planning. Initially, the grid operator determines how many and which power transformers will be maintained. In a second step, they calculate the best route for the technicians. This is a common problem in operations research – the travelling salesman problem (Miller et al. 1960). Its complexity determines whether to apply heuristics (Rego et al. 2011) or algorithms providing the exact solutions (Padberg and Rinaldi 1991). The maintenance staff should receive the information on mobile devices to communicate short-term changes due to urgent incidents. The devices can be used as well to directly transfer the maintenance reports to the database.

The predictions of the transformer status are also applied for investment planning. High-voltage power transformers have long delivery times which requires long-term planning of replacement investments. However, over-capacities must be avoided because of the high investment costs and the regulated budget of distribution system operators. Predictive maintenance must enable an optimal investment strategy under these restrictions.

4. Results system impact quantification

Potential cost savings are the main motivation for applying predictive maintenance on electricity infrastructure. The information gain shall improve asset operation and maintenance and investment planning which could reduce the costs for electricity grid operation. Even though the cost savings are low compared to the necessary grid expansion (Consentec and Fraunhofer ISI 2018), it can still result in a discount of the grid fees. Additionally, it might have positive effects on security of supply as it can prevent transformer outages by early detection of critical wear parts. The potential lifetime extension can reduce greenhouse gas emissions and the material demand of replacement investments. To quantify the system impact of predictive maintenance, we consider a Germany-wide application on high-voltage transformers with approximately 7500 assets according to the latest publicly available census (VDN 2007).

4.1. Competitiveness

The profitability assessment of predictive maintenance compares potential savings with newly induced costs. The gains consist reduced maintenance cost and overall lower replacement investments through lifetime extensions. On the one hand, additional costs are directly related to the purchase and installation of ICT, such as costs for sensing equipment and personnel costs for implementation. On the other hand, lifetime extensions can induce opportunity costs if operational losses of the old transformer exceed the ones of a newly purchased one. The calculation of the total cost savings per year reads:

$$\begin{aligned} \mathit{Cost\ Savings} = {} & \mathit{Reduced\ Maintenance\ Costs} + \mathit{Reduced\ Investment\ Costs} \\ & - \mathit{Costs\ Additional\ Trafo\ Losses} - \mathit{ICT\ Purchase\ and\ Installation\ Costs} \\ & - \mathit{Additional\ Personnel\ Costs} \end{aligned}$$

$$\begin{aligned} = {} & \mathit{Reduced\ Maintenance\ Costs} + \mathit{Reduced\ Replacement\ Investments} * \mathit{Investment\ Costs} \\ & - \left(\mathit{Efficiency}_{new\ Tafo} - \mathit{Efficiency}_{old\ Tafo}\right) * \mathit{Trafo\ Load} * \mathit{Electricity\ Price} \\ & * \mathit{Reduced\ Replacement\ Investments} - \mathit{ICT\ Purchase\ and\ Installation\ Costs} \\ & - \mathit{Additional\ Personnel\ Costs} \end{aligned}$$

All components are displayed in Table 1 with the assumptions and their calculation being described in greater detail in the following paragraphs.

Table 1: Overview of economic evaluation of predictive maintenance for power transformers.

[million €/year]		**Lifetime extension**		
		1 year	**5 years**	**10 years**
Gains	**+ reduced maintenance costs**	8		
	+ reduced investment costs	10.7	49.8	91.3
Costs	**- increased losses old transformer**	< 0.25	< 1.2	< 2.1
	- ICT purchase and installation / personnel	no information available		

The savings of maintenance costs result from the individually fitted maintenance periods. The effort is increased for critical assets but reduced for transformers with lower risks which shall decrease the total expenditures. There are no independent evaluations regarding the overall potential of that approach. But according to a case study of the transformer manufacturer ABB (Westman et al. 2010), a predictive maintenance strategy was able to reduce the yearly maintenance costs of a customer with 128 transformers by € 275,000 which is probably an optimistic estimate of the potential. However, if this is representative, the Germany-wide potential is up to € 16 million per year. This would require an implementation for all distribution grid operators which is currently unlikely. Developing the model is time intensive and probably not beneficial for operators with a small portfolio. This could change if independent service providers would be able to transfer methods and model configuration from one grid area to another. Essentially this means that € 16 million is the ceiling for the total savings of maintenance costs. We take a more conservative assumption of € 8 million savings per year.

Calculating the Germany-wide cost savings for replacement investments needs an estimation of the investment costs for high-voltage transformers. The costs vary widely as each transformer is set up individually. As grid operators and regulators do not publish reliable data, we fall back to information from case studies of manufacturers. Siemens (2014) estimate costs of € 2.75 million for the asset itself which is in line with Westman et al. (2010). The latter source adds costs of around € 0.8 to 1.0 million for disposal of pollutants from the old transformer, labor costs for installation and implementation and expenses for individual specifications. So, the average costs of a replace investment sum up to € 3.65 million. Additionally, we need an average asset lifetime. According to the manufacturer ABB, there are critical failure rates after 50 years of operation (Westman et al. 2010). We assume a uniform age distribution of the installed transformers which would result in 150 replacements per year as a baseline. Finally, we analyze the system impact of a lifetime extension between one and ten years. This sensitivity analysis is necessary as there are no data on the potential impact of predictive maintenance on asset lifetime. If the lifetime could be enlarged by one year, the total number of reinvestments per year reduces by three leading to a cost reduction of € 10.7 million per year. A lifetime extension of all installed transformers by ten years enables savings of ten transformers per year which is worth 91.3 million per year.

On the other hand, lifetime-extension can be a cost factor, too. Older transformers usually cause higher total power losses that are given by the sum of load and no-load losses. The necessary magnetization of the ferrite rod causes losses being independent from the transformer load. Load losses are associated with the coils and increase quadratic with the transformer load (Jorge et al. 2012). Therefore, the calculation of the total losses requires an assumption of a load profile. The final costs are the product of the power losses and the electricity price (Wachter 2017). As there is no publicly available information on transformer load profiles, we estimate the potential costs with a constant load of 50 %. Having a high-voltage transformer of 50 MVA and an average electricity price of € 37.70 per MWh (average day ahead price in Germany for 2019 (EPEX SPOT 2019)), a lower efficiency of 0.1 percentage points would cause a yearly loss of € 8250. The total losses of state-of-the-art transformers are below 0.5 % (Jorge et al. 2012). The relevant literature does not provide a development of the efficiency depending on the year of constructions which allows only a qualitative evaluation. No-load losses have been strongly reduced by the technological progress during the 1950s and 1960s. However, most of the currently used high-voltage transformers have been installed later when there have been no significant efficiency improvements (Belmans et al. 2005). Moreover, the losses for magnetization of the ferrite rod cause only 15 % of the total losses (Jorge et al. 2012). There are also no large enhancements of the materials of the coil windings in recent years so that load losses have been relatively stable (Belmans et al. 2005). To sum up, it can be assumed that the efficiency has been improved only by a few tenths of percentage points. Even assuming an average efficiency gain of one percentage point, the economic costs would be below € 0.25 million for an average lifetime extension of one year (representing three reduced replacement investments) and below € 2.1 million for an average lifetime extension of ten years (representing 25 reduced replacement investments).

Finally, costs directly associated with ICT, such as cost for data collection and integration efforts as well as the creation or purchase of software for the state prediction and respective maintenance planning must be considered. This share of costs is highly individual depending on the company and its infrastructure which makes robust and generally valid estimates in fact impossible. The expert interview revealed, however, that personnel costs are usually higher than the expenses for hardware and software (Koch, Letzgus 11/16/2018). Looking at the cost overview in Table 1 shows, that system wide ICT implementation costs in between € 18.5 million and € 97.7 million, depending on the assumption of average lifetime-extension, would be economically justified.

4.2. Environmental sustainability

The assessment of the environmental sustainability is based on a life cycle assessment (LCA) to consider the ecological effects of the materials, manufacturing, installation and operation. We do not consider the positive environmental impact of the reduced maintenance as it has only a minor impact compared to the replacement investment (Jorge et al. 2012). At the same time, we also neglect the impact of the required ICT installations, because the solutions are highly individual, often used across applications and overall magnitudes smaller than the considered effects on the power transformer hardware.

The study of Jorge et al. (2012) provides an LCA for different transformers and substation equipment. It is based on life cycle inventories of equipment from ABB. There are high-voltage transformers of 40, 50 and 63 MVA (ABB 2003a, 2003b). It can be assumed that their ecological impact is comparable to current transformers as it is a matured technology (Belmans et al. 2005). In the following analysis we focus on the impact categories global warming potential and metal depletion as major representatives for the sustainability evaluation.

The three transformer types cause greenhouse gas emissions from 16.2 to 23.9 kilotons CO_2-equivalents over the whole life cycle (Table 2). 98 % of these emissions are associated with power losses during operation even though the efficiency is at 99.54 %[1]. So, providing the infrastructure generates 0.6 kilotons CO_2-equivalents on average. During the economic assessment, we determined a lifetime extension between one and ten years as boundaries for a sensitivity analysis which enables savings of three or ten transformer replacements per year. So, the avoided new acquisitions may reduce the emission of greenhouse gases between 1.22 and 10.3 kton CO_2-equivalents per year.

Table 2: Ecological impact of high voltage transformers. Source: Jorge et al. (2012).

		Transformer capacity			
		40 MVA	**50 MVA**	**63 MVA**	**Average**
Greenhouse gas emissions	**Total (kton CO_2-eq)**	16,22	21,9	23,86	20,66
	Share operating phase	98 %	98 %	98 %	98 %
	Infrastructure (kton CO_2-eq)	0,32	0,44	0,48	0,41
Material demand	**Total (ton Fe-eq)**	0,42	0,45	0,61	0,49
	Share operating phase	24 %	29 %	29 %	27 %
	Infrastructure (ton Fe-eq)	0,32	0,32	0,43	0,36

---

[1] Jorge et al. (2012) assume an asset lifetime of 35 years and an average load of 50 %. The emissions during operation phase are based on an average European power mix without giving the reference year.

On the other hand, older, inefficient transformers would be used for a longer time. So, regarding greenhouse gas emissions, the environmental sustainability depends on the individual efficiency gains of a new transformer. Figure 6 illustrates the relation when assuming an efficiency of 99.54 % for the new transformer as in Jorge et al. (2012). Even a lifetime extension of one year requires an efficiency of 99.2 % for break-even emissions. A lifetime extension of ten years makes only sense if the old transformer has an efficiency of 99.5 %. However, the greenhouse gas emissions during utilization strongly depend on the electricity generation technologies. Jorge et al. (2012) take an average European power mix without giving the reference year or the average CO_2-emissions. A further decarbonization of the electricity generation would cause a shift to lower thresholds.

The material demand is predominantly associated with raw material production. The share of the operation phase is at 27 % on average. It results from the additional generation capacity which is necessary to cover the power losses of the transformer. Considering a recycling rate of 70 % (ABB 2003a, 2003b), a new transformer requires between 0.32 and 0.43 tons iron equivalents.[2] Assuming a uniform distribution of the three transformer types, an average lifetime extension between one and ten years leads to Germany-wide savings between 1.05 and 8.93 ton iron equivalents per year. Since most of the material demand is associated with the production, calculations showed that from a metal depletion point-of-view it is beneficial to use old transformers as long as possible (Figure 6).

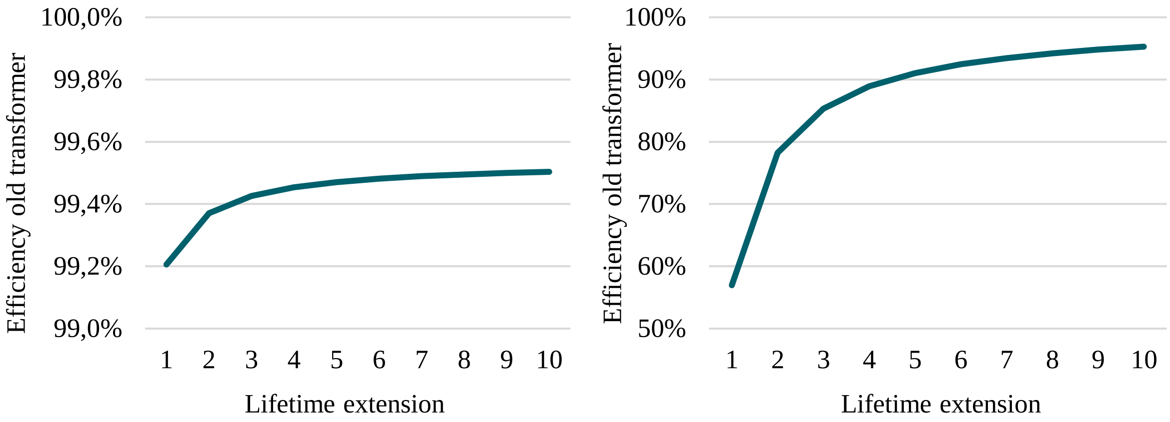

Figure 6: Ecological lifetime extension with regard to greenhouse gas emissions (left) and material demand (right) depending on the efficiency of the old transformer. Own calculations based on Jorge et al. (2012).

4.3. Security of supply

In the search for pareto-optimal solutions, financial benefits for grid users shall not have a negative impact on their security of supply. An outage of a high-voltage power transformer is a realistic scenario but happens rarely. The preventive maintenance scheme allows to detect damages at an early stage and repair or replacement actions can be initiated before heavy damages arise (Koch, Letzgus 11/16/2018). Nevertheless, it is assumed that a good predictive maintenance strategy can save costs by removing inefficiencies in the maintenance procedure without compromising on security of supply. In fact, grid design in many countries, such as Germany, follows the principle of redundant high-voltage power transformers. Consequently, the outage of a power transformer does not necessarily lead to an interruption of power supply if grid operators can initiate necessary compensatory measures quickly. Thus, predictive maintenance is not expected to have an impact on the System Average Interruption Duration Index (SAIDI), the central KPI for security of supply of an electricity grid.

---

[2] There are several LCA methods to consider the value of different minerals for calculating the metal depletion. They are based inter alia on assumotions of ressources and reserves or exergy losses (Klinglmair et al. 2014). Jorge et al. (2012) use the method ReCiPe 2008 which reflects the additional marginal cost increase to extract a resource from more expensive mines. The characterization factors are devided by the factor of iron to enable the summation of different materials (Goedkoop et al. 2009).

4.4. Summary

The analyses show the potential of ICT to enable a convergence towards a pareto-optimal solution for predictive maintenance of high voltage transformers.

Table 3 provides an overview of the system impact for all three energy policy dimensions.

Table 3: Overview of system impact of predictive maintenance for high voltage transformers. Own calculations based on Westman et al. (2010), Siemens (2014) and Jorge et al. (2012).

Dimension	Indicator	System impact
Competitiveness	Total costs	Avoided maintenance costs: € 8 million per year (up to € 16 million) Avoided investment costs: € 10.7 to 91.3 million per year Additional costs power losses: € 8250 per year per 0.1 percentage points (50 MVA transformer with 50 % average load) Additional costs for implementation: Not specified
Environmental sustainability	Greenhouse gas emissions	Greenhouse gas savings by avoided replacements: 1.22 to 10.3 kilotons CO_2 equivalents per year Advantage of lifetime extension depends on potential efficiency enhancement of new transformer
	Material demand	Material savings by avoided replacements: 1.05 to 8.93 tons Fe equivalents per year Positive impact of lifetime extension
Security of supply	SAIDI	No impact expected

5. Conclusions

Measuring the effect of ICT on system efficiency is a highly complex task. It appears necessary to address individual challenges for a qualitative and quantitative evaluation of the system impact. This paper has introduced a method to evaluate ICT contributions to specific energy system related tasks. The first step is to analyze the potential of an ICT based process improvement including ICT-related challenges for each process step. If ICT helps to enable additional potentials it is possible to analyze the system impact. For this purpose, it is necessary to consider all three energy policy goals.

Applying this method to the predictive maintenance of power transformers shows potential to lower the total system costs. It can reduce the maintenance costs by up to € 16 million per year. Assuming a lifetime extension between one and ten years, the savings for replacement investments are between € 10.7 and 91.3 million per year. Even though the additional costs for implementation of predictive maintenance are not specified, it is very likely that predictive maintenance is beneficial for grid operators which would reduce the grid fees. The impact on the material demand is positive as well. The material savings by avoided replacements are between 1.05 and 8.93 tons iron equivalents per year. The contribution to the global warming potential is highly affected by the energy losses during utilization of the power transformers. The potential efficiency gains influence the ecological benefit of a longer usage of existing transformers. Even a lifetime extension of one year requires an efficiency of 99.2 % for the old transformer to be break-even on greenhouse gas emissions. Even though predictive maintenance can help to prevent outages by an earlier detection of critical wear parts, there is no expected impact on security of supply due to the redundantly designed electricity grid. In summary, while the saving potential of predictive maintenance is rather small compared to the system wide costs and ecological impact, it still helps to improve the footprint of maintenance and investment planning of energy infrastructure.

References

A.T. Kearney; Bundesverband der Energie- und Wasserwirtschaft (BDEW); IMProve (2018): Digital@EVU. Wo steht die deutsche Energiewirtschaft? Available online at https://www.bdew.de/media/documents/201802_Paper-Digital-EVU.pdf, checked on 12/6/2019.

ABB (2003a): Environmental Product Declaration. Large Distribution Transformer 40/50MVA (ONAN/ONAF). Edited by Italy Milano. Mailand.

ABB (2003b): Environmental Product Declaration. Power transformer TrafoStar 63 MVA. Ludvika.

Alpaydin, Ethem (2010): Introduction to machine learning. 2nd ed. Cambridge, Mass: MIT Press (Adaptive computation and machine learning). Available online at http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=307676.

Azadeh, Ali; Abdolhossein Zadeh, Saeed (2015): An integrated fuzzy analytic hierarchy process and fuzzy multiple-criteria decision-making simulation approach for maintenance policy selection. In *SIMULATION* 92 (1), pp. 3–18. DOI: 10.1177/0037549715616686.

Belmans, Ronnie; Declerq, Jan; Keulenaer, Hans de; Furuya, Katsuaki; Karmarkar, Mayur; Martinez et al. (2005): The Potential for Global Energy Savings from high Efficiency Distribution Transformers. Edited by European Copper Institute. Brüssel. Available online at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.549.3044&rep=rep1&type=pdf, checked on 11/1/2019.

DIN VDE 0105-100: Betrieb von elektrischen Anlagen. Available online at https://www.vde-verlag.de/normen/0100285/din-vde-0105-100-vde-0105-100-2015-10.html, checked on 10/16/2019.

Consentec; Fraunhofer ISI (2018): BMWi-Vorhaben „Netzentgelte“. Auswertung von Referenzstudien und Szenarioanalysen zur zukünftigen Entwicklung der Netzentgelte für Elektrizität. Available online at https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/netzentgelte-auswertung-von-referenzstudien.pdf?__blob=publicationFile&v=6, checked on 10/16/2019.

Devlin, Barry (2000): Data warehouse. From architecture to implementation. 6. printing. Reading, Mass.: Addison-Wesley.

EPEX SPOT (2019): Market data. Available online at https://www.epexspot.com/en/market-data, checked on 2/6/2020.

Gill, Paul (2009): Electrical power equipment maintenance and testing. 2nd ed. Boca Raton: CRC Press (Power engineering, 32). Available online at http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10285366.

Goedkoop, Mark; Heijungs, Reinout; Huijbregts, Mark; Schryver, An De; Struijs, Jaap; van Zelm, Rosalie (2009): ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First Edition. Report I. Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. Available online at https://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf, checked on 11/6/2019.

Imani, Mohammad Taghi; Homeier, Kristin; Werle, Peter; Dräger, Gerald (2018): Furane als Alterungsindikatoren für die Zustandsbestimmung der Zellulose in ölgefüllten Transformatoren. In : VDE-Hochspannungstechnik. Berlin: VDE-Verlag. Available online at https://www.vde-verlag.de/proceedings-de/454807044.html, checked on 10/15/2019.

Jorge, Raquel Santos; Hawkins, Troy R.; Hertwich, Edgar G. (2012): Life cycle assessment of electricity transmission and distribution—part 2. Transformers and substation equipment. In *Int J Life Cycle Assess* 17 (2), pp. 184–191. DOI: 10.1007/s11367-011-0336-0.

Klinglmair, Manfred; Sala, Serenella; Brandão, Miguel (2014): Assessing resource depletion in LCA. A review of methods and methodological issues. In *Int J Life Cycle Assess* 19 (3), pp. 580–592. DOI: 10.1007/s11367-013-0650-9.

Koch, Christopher; Letzgus, Simon (11/16/2018): Experteninterview „Intelligentes Energiesystem“. Intelligente Netzinstandhaltung. Interview with Philipp Clasen. Berlin.

Mieg, Harald A.; Näf, Matthias (2006): Experteninterviews in den Umwelt- und Planungswissenschaften. Eine Einführung und Anleitung. Lengerich: Pabst Science Publ. Available online at http://deposit.d-nb.de/cgi-bin/dokserv?id=2875666&prov=M&dok_var=1&dok_ext=htm.

Miller, C. E.; Tucker, A. W.; Zemlin, R. A. (1960): Integer Programming Formulation of Traveling Salesman Problems. In *J. ACM* 7 (4), pp. 326–329. DOI: 10.1145/321043.321046.

Padberg, Manfred; Rinaldi, Giovanni (1991): A Branch-and-Cut Algorithm for the Resolution of Large-Scale Symmetric Traveling Salesman Problems. In *SIAM Rev.* 33 (1), pp. 60–100. DOI: 10.1137/1033004.

PricewaterhouseCoopers International (PWC) (2018): Mit Künstlicher Intelligenz gegen den Klimawandel. Available online at https://www.pwc.de/de/nachhaltigkeit/studie-mit-kuenstlicher-intelligenz-gegen-den-klimawandel.html, checked on 12/6/2019.

Rego, César; Gamboa, Dorabela; Glover, Fred; Osterman, Colin (2011): Traveling salesman problem heuristics. Leading methods, implementations and latest advances. In *European Journal of Operational Research* 211 (3), pp. 427–441. DOI: 10.1016/j.ejor.2010.09.010.

Siemens (2014): Leistungstransformatoren. Maschinen- und Netztransformatoren von 30 bis über 1.300 MVA. Available online at https://w5.siemens.com/web/at/de/energy/trafo-linz/home/Documents/E50001-G640-A241%20Leistungstransformatoren%20von%2030%20bis%20%C3%BCber%201300MVA.pdf, checked on 10/30/2019.

VDN (2007): Stromnetz in Deutschland. Daten und Fakten 2007. Berlin.

Vogel, Lukas; Richard, Philipp; Brey, Michael; Mamel, Sara; Schätz, Konstantin (2019): Künstliche Intelligenz für die integrierte Energiewende. Deutsche Energie Agentur GmbH (dena). Available online at https://www.dena.de/newsroom/publikationsdetailansicht/pub/dena-analyse-kuenstliche-intelligenz-fuer-die-integrierte-energiewende/, checked on 12/6/2019.

Wachter, Bruno de (2017): Application Note MV Transformer Replacement Decision. Available online at https://de.slideshare.net/sustenergy/mv-transformer-replacement-decisions, checked on 2/6/2020.

Westman, Thomas; Lorin, Pierre; Ammann, Paul (2010): Fit mit 50. Verlängerung der Lebensdauer alternder Transformatoren mit ABB TrafoAsset Management-Proactive Services. ABB. Available online at https://library.e.abb.com/public/7aeb01454159c2b6c12577bb0036a359/ABB_Review_Fit_at_50_German.pdf, checked on 10/30/2019.