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Developing an Environmental Management Information System to Foster Sustainable Decision-Making in the Energy Sector

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DEVELOPING AN ENVIRONMENTAL MANAGEMENT INFORMATION SYSTEM TO FOSTER SUSTAINABLE DECISION-MAKING IN THE ENERGY SECTOR

Complete Research

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Abstract

We develop an environmental management information system (EMIS) that provides economic and environmental data to suppliers and consumers of electrical energy. This information-sharing fosters sustainable decision-making in accordance with individual preferences and results in time-shifting energy consumption, which ultimately improves the alignment of power supply and demand. In turn, this enhances the integration of renewable energy systems, reduces the use of fossil fuels, and increases energy efficiency. We develop the EMIS based on established architectures and embed it into the Energy Informatics Framework, where it is supposed to operate at the interface of energy supply and demand in a smart grid environment. To conceptualize, design, and evaluate the developed system, we rely on the well-acknowledged research methodology of design science. In line with that, we demonstrate the utility of the EMIS and discuss its benefits regarding sustainability aspects by means of a comprehensive scenario analysis. To sum up, the proposed EMIS applies the promising integration of energy and IS research by means of Energy Informatics and responds to the necessity of incorporating environmental sustainability aspects into both corporate and consumer decision-making.

Keywords: Environmental management information system, Energy Informatics, Sustainability, Design Science.

1 Introduction

The pursuit for sustainable development is indisputably one of the great challenges of the 21st century. It aims to permanently meet the basic needs of all and, thus, ensures present and future generations a better life (Brundtland, 1987). Following the popular concept of the ‘triple bottom line’, sustainability consists of economic, ecological, and social dimensions (Dyllick and Hockerts, 2002; Elkington, 1998). In this context, a major challenge is fostering the use of energy sources that are dependable, safe, and environmentally sound. In particular, this urges for reducing the combustion of fossil fuels, integrating renewable energies into energy supply chains, and increasing energy efficiency (Lund, 2007). These tasks pose a spectrum of new requirements to energy systems, which are supposed to become more intelligent and experience a change towards so-called ‘smart grids’ (Farhangi, 2010). Even though information systems (IS) are seen as a prerequisite for smart grids (Hadjsaïd and Sabonnadière, 2012) and as a major enabler to meet the stated challenges of sustainability (Watson et al., 2010), leveraging synergies from combining the research fields of IS and energy management while explicitly including an environmental perspective has been widely neglected. Accordingly, a need for “the design of innovative information systems for energy monitoring, […] the antecedents of use of energy optimization systems, and understanding of the impact of demand response on energy markets and peak load requirements” exists (Melville, 2010, p. 2). To respond to these needs, only in recent years the term ‘energy informatics’ (EI) has been established and defined as “analyzing, designing, and implementing systems to increase the efficiency of energy demand and supply systems" (Watson et al., 2010). The ultimate goal of this interdisciplinary approach is unleashing the potentials of merging information technologies and energy systems to achieve sustainability targets.

One way to address and support sustainable decision-making in a corporate context is introducing environmental management information systems (EMIS), which have already proven their value in the discipline of (sustainable) supply chain management (Stindt et al., 2014). On the one hand, a look into business practice reveals a dearth of energy management systems that explicitly gather, process, and distribute environmental information to supplying and demanding actors (Connolly et al., 2010), although it is mandatory to create more sustainable energy systems. On the other hand, approaches that could serve as a basis for practical solutions to improve this situation are barely provided by academia. Therefore, we concentrate on integrating the environmental dimension of sustainability into energy management and state our guiding research question as follows:

How can environmental-oriented decision-making in the energy sector be fostered by an integration of energy management and information systems?

Against this background, we propose the concept of an EMIS that expands established energy management systems (EMS) with an environmental perspective. The EMIS complements Demand Side Management (DSM) systems that mostly rely on economic incentive setting. It operates at the interface of power supply and demand and considers economic, ecological, technical, and legal factors. The EMIS provides necessary economic and especially environmental data to participating actors (energy suppliers, 'economic' consumer segments, 'green' consumer segments), who make decisions on that basis of information following individual preferences. In doing so, a time-shift of demands is induced, which is an essential part of fostering sustainability in the energy sector (Corbett, 2011) as it ultimately improves balancing of power supply and consumption. This leads to a better integration of renewable energy sources, reduces the usage of fossil fuels, and increases energy efficiency. The EMIS is developed based on literature following a well-known research methodology in IS, namely the design science paradigm (Hevner et al., 2004; Peffers et al., 2007).

The remainder of the article is structured as follows: In section 2, we present the fields of EI and DSM, describe the concept of an EMIS for the energy sector, and review existent approaches that incorporate environmental aspects into IS-based decision-making in energy systems. The underlying research methodology is depicted in section 3. In section 4, we develop the EMIS and present its architecture in detail. Subsequently, we demonstrate its applicability and discuss its benefits in section 5. Finally, in section 6 we draw a conclusion, summarize key findings, and provide a research outlook.

2 Towards a new paradigm – the road to a more sustainable energy sector

Developments in recent years have placed a new set of requirements to the electricity grid, which forms a vital part of the energy sector. In particular, the integration of renewable energy supply systems, such as wind and solar energy, poses a spectrum of new challenges to grid management, including uncertainty over production levels, increasingly distributed generation points of low voltages, and short-term significant changes in network energy flows, amongst others (Coullon, 2012). The introduction of smart grids, which are roughly defined as "an integration of electricity infrastructure and the embedded/decentralized ICT (software, automation and information processing)" (Hadjsaïd and Sabonnadière, 2012, p. 17), may provide solutions to the challenges stated above. Compared with traditional electricity grids that are operated "unidirectional and top-down oriented" (Palensky and Dietrich, 2011, p. 381), one of the "most significant changes is the availability of new and multidirectional information flows" (Corbett, 2011, p.2). To efficiently manage the interplay of power supply, smart grids, and power consumption in terms of economic and ecological goals, an advanced integration of energy management and IS is proposed, which leads to the emerging field of EI (Kossahl et al., 2012; Watson et al., 2010).

EI is seen as a major enabler to properly incorporate sustainability issues into the energy sector (Watson et al., 2010). Nevertheless, against the background of a generally observed disintegration of research on (corporate) environmental sustainability and IS (Melville, 2010; Schmidt et al., 2009; Thambusamy and Salam, 2010), the nascent field of EI is “a new domain of inquiry” (vom Brocke et al., 2013, p. 1), yet producing a growing research output (e.g. Califf et al., 2012; Feuerriegel et al., 2013). Several subtopics of EI are proposed for future research (Kossahl et al., 2012). In the context of developing adequate IT-architecture and related data transmission, research efforts focus on DSM systems, including Demand Response (DR) systems. The purpose of DR systems is altering consumption patterns due to economic factors, such as price changes or incentive payments (FERC, 2012). Recent publications underline the potential economic benefits of using such systems (Feuerriegel and Neumann, 2014; Feuerriegel et al., 2013) and integrate DR into the EI framework (Feuerriegel et al., 2012). Nevertheless, a systematic sharing of environmental information and its effect on time-shifting of electricity demand is not considered. In fact, the distribution of environmental data seems to be neglected by contemporary DMS and DR systems (Aghaei and Alizadeh, 2013; Jalali and Kazemi, 2015). Consequently and to the best of our knowledge, IT solutions that explicitly provide environmental data to all relevant stakeholders in the energy sector by means of an EMIS do not exist (Connolly et al., 2010).

An EMIS is defined as an “organizational-technical system for the systematic gathering, processing, and provision of environmental information in a company” (Loos et al., 2011, p. 247) to foster sustainable development (Teuteberg and Marx Gómez, 2010). A tailored system for the energy sector can be seen as an application of EI and as a special form of a DSM system (Palensky and Dietrich, 2011). Although EMIS are proposed for other domains and industry sectors, like sustainable supply chain management in the electronics industry (Stindt et al., 2014), these systems cannot be transferred to the energy sector without taking its specific characteristics into account. This includes, for instance, real-time balancing of power supply and demand in electricity grids by means of adequate IS. To exploit the multi-directional nature of smart grids, an EMIS that operates at the interfaces of energy demand and supply should particularly provide environmental information not only to corporate decision-makers, but also to consumers of electricity. The latter extends the above given definition of an EMIS. Going beyond the technical dimension, such information-sharing aims at promoting eco-conscious behavior, which alters consumption patterns of electricity (e.g. through time-shifting demands) to better match current energy supply, which increases efficiency (Corbett, 2011). This is in line with research suggesting the development of IS that actively influence individual consumption patterns (Melville, 2010). Interestingly, few publications exist that investigate possible positive impacts on altering energy demand patterns through IS-based communication of environmental data (Loock et al., 2013), although the value of environmental information for consumer decision-making independent of the considered product or services is stressed (Watson et al., 2012). The realization of a sustainable lifestyle is difficult for consumers as “they lack information about the environmental consequences of their choices” (Watson et al., 2012, p. 12). In the context of the energy sector, such information could comprise, for example, CO_2 emissions that result from the current energy mix.

The proposed EMIS aims at solving the described discrepancy through distributing economic and environmental information to both suppliers and consumers of electricity. Hence, all participants are ultimately able to make decisions on that basis of information and in accordance to their individual preferences and objectives. This may lead to an improved alignment of power supply and demand as well as to more sustainable energy systems.

3 Research methodology

To effectively answer the stated research question, we select the ‘applied design science research model’ (Bensch, 2012). It combines a well-known methodology, namely the ‘design-science research methodology process model’ (Peffers et al., 2007), and guidelines for design-science research (Hevner et al., 2004). The paradigm of design-science is well suited for the identified problem as it aims at “creating and evaluating innovative IT artifacts that enable organizations to address important information-related tasks” (Hevner et al., 2004, p. 98). Moreover, it has proven its value in similar contexts (e.g. Bodenbenner et al., 2013; Stindt et al., 2014). We describe the implementation of this generic approach for the purpose of the present research in the following.

Step 1 – Identify problem and motivate: We select a problem-centered initiation as research entry point. More specifically, we identify the urgency of incorporating environmental aspects into decision-making processes within the energy sector. There is a broad consensus that IS play a major role in ultimately driving the energy sector towards a more sustainable development (Watson et al., 2010). Although this positive lever is widely accepted in academia, up to now little efforts have been made to propose actual IS to realize this potential (see sections 1 and 2).

Step 2 – Define Objectives of a Solution: Against the background of the stated research question, we seek to develop an EMIS that fosters environmental-oriented decision-making among actors in the energy sector. The overarching goal is to create more sustainable energy systems. In this context, we define measurable objectives of a solution: The EMIS should improve the balancing of power supply and demand, which in turn leads to a better integration of renewable energy systems, a reduced use of fossil fuels, and increased energy efficiency.

Step 3 – Design and Development: The designed artifact is the proposed EMIS, which we integrate into the Energy Informatics Framework (Watson et al., 2010). The conceptual model of the EMIS is developed within section 4 and bases on three layers. Hereby, we rely on sustainability-oriented approaches in IT-architecture design (Stindt et al., 2014; Teuteberg and Marx Gómez, 2010). We describe each layer in detail against the background of specific requirements placed on an EMIS designed for the energy sector.

Step 4 – Demonstration & Evaluation: To give first evidence about the utility of the designed artifact, the value of the EMIS is demonstrated within a scenario-based setting that is partly based on real-world data derived from secondary sources (e.g. scientific knowledge base, public databases) (section 5). This evaluation method is in line with approaches in similar contexts (e.g. Feuerriegel et al., 2013). Within the presented study, the EMIS is assumed to operate at the interface of power supply and demand and balances both sides by a systematic communication of economic and environmental information. We exemplify the benefits of the EMIS in this realistic environment and discuss the achievement of the objectives set within *Step 2*.

Step 5 – Communication: By means of the present article, we communicate our key research findings that are summarized within section 6 to the IS community. In addition, we critically assess our work and give ideas for further research efforts.

4 Conceptual model of EMIS

The subsequently developed EMIS is supposed to operate at the interface of energy demand and supply as both sides “should share a common information system to ensure a cohesive solution” (Watson et al., 2010, p. 25). Hence, we embed the EMIS into the Energy Informatics Framework where it links energy generation and transmission/distribution with energy consumption. Specific entities are located on both sides, namely plant control, sensor networks, flow networks, and corporate IS are located on the supply side. On the demand side, sensitized objects, like smart metering systems and energy controllers, represent consumers' assets. To share information with the EMIS, entities are interconnected and linked to the EMIS via data buses and field buses. As already mentioned, the proposed EMIS exploits the benefits of multi-directional communication in smart grids. Thus, information flows are continuously looped to the entities of both the supply and the demand side. On the supply side, the decision data and information of the EMIS are used to adjust power plant outputs as well as to control electricity flow networks. For data exchange and communication between entities on the supply side and the EMIS we propose TCP/IP Transport with IEC 61850 and its associate standards (Farhangi, 2010). On the demand side, we suggest implementing an advanced metering infrastructure using a standard for smart metering, e.g. ANSI 12.22 (Farhangi, 2010). In this way, EMIS information is shared with consumers respectively with their sensitized objects to provide decision-support regarding demand patterns. The overall system with the embedded EMIS is depicted within Figure 1.

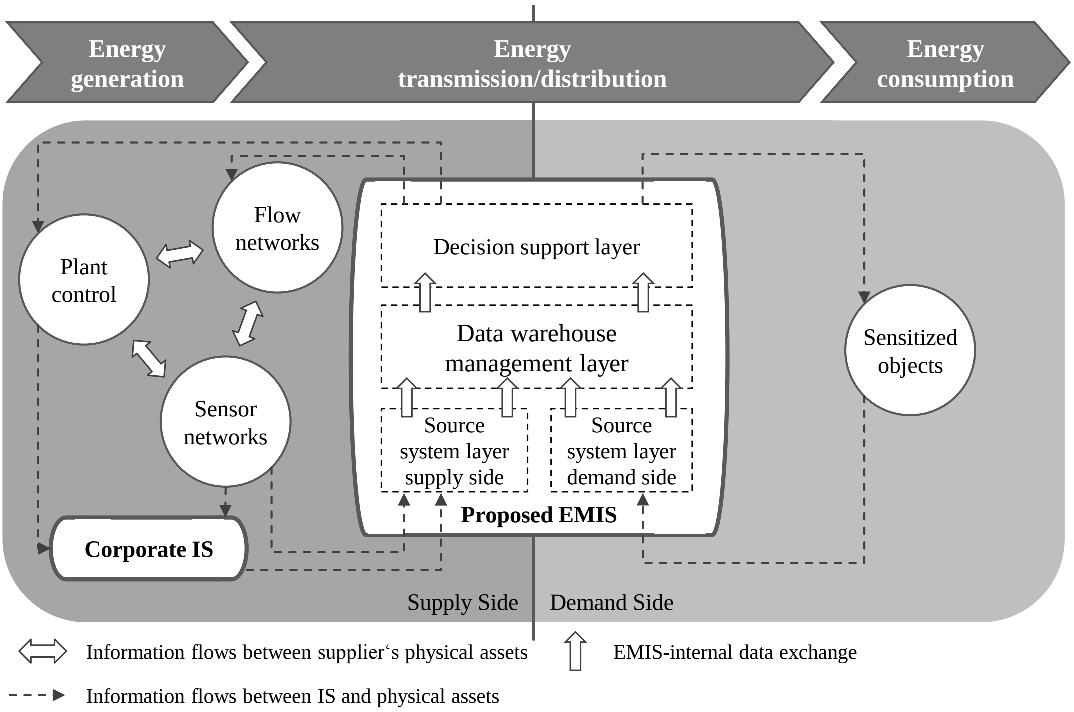

Figure 1. EMIS embedded into the Energy Informatics Framework following Watson et al. (2010).

The EMIS is based on reference architectures for such systems (Stindt et al., 2014; Teuteberg and Marx Gómez, 2010). It addresses the explicit need for developing an IT-architecture with its respective layers to process, analyze, and transmit data flows in an effective and efficient way (Kossahl et al., 2012). During the development of the conceptual model, we particularly emphasize componentization and standardized data exchange formats between EMIS-internal layers, as such aspects "improve the reuse and integration of EMIS with other systems within the organization" (El-Gayar and Fritz, 2006, p. 773). This facilitates, for instance, the integration of additional source systems. We note that the EMIS is designed as an automatically operating system that expands established EMS and, thus, is owned and operated by the energy supplier. We describe the architecture of the EMIS, especially its three-tier layer structure as well as its intra-system interfaces and communication flows, in the following. The EMIS architecture is illustrated in detail in Figure 2.

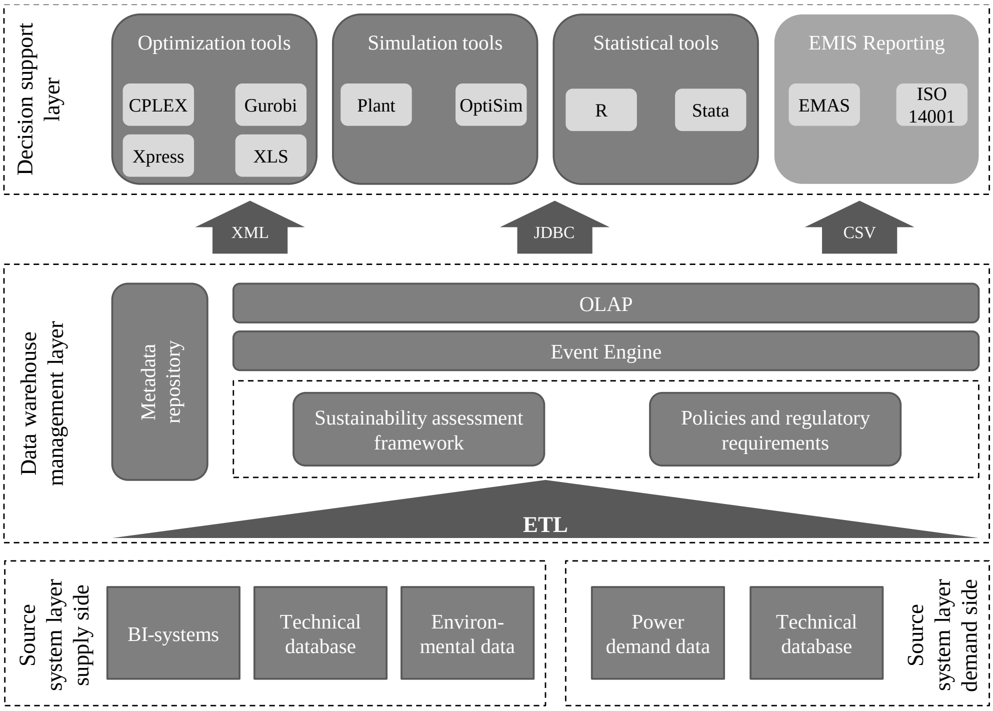

Figure 2. Architecture of EMIS.

4.1 Source system layer

Within the source system layer all relevant information is integrated into the EMIS. Owing to the interfacial character of the system, the layer is split to link to data sources from both the supply and demand side.

On the supply side, corporate IS and sensor networks are linked to the EMIS. In this way, business intelligence (BI) systems, technical databases, and environmental data are integrated. BI-systems may comprise both the enterprise resource planning (ERP) system and existing EMS. Relevant information obtained from these sources mainly encompasses revenue and cost data, which consist of cost structures regarding electricity generation, transmission, and transformation (e.g. losses from high-voltage to medium-voltage transformation). The link to technical databases feeds the EMIS with infrastructural information regarding all technical assets that are needed to properly generate, control, and transmit electricity. This includes the general grid topology and available power plants, power generation capacities of different sources and their degree of scalability, and available energy storages like pumped-storage plants or a network of electric vehicles (Brown et al., 2010). For instance, energy produced with renewable sources is exogenously determined and only partly capable of providing base load power, while base-load plants are inflexible, hardly adjustable in the short term, and work at decreased efficiency when operated at part-load levels (Troy et al., 2010). In addition, collected technical data emanating from the sensor network are integrated, which provide information concerning current plant loads and grid loads. This is mandatory for subsequent flow optimization (Watson et al., 2010) and for ensuring grid stability. Environmental data are mostly provided to the EMIS through connecting to sensor networks. Related information includes weather forecasts that are important to predict renewable energy supply (Hammons, 2008; Potter et al., 2009) and, in particular, pollutant emissions (e.g. CO_2, SO_2, NO_x) from used energy sources, which are mandatory for the concept of an EMIS.

On the demand side, the consumers' sensitized objects transfer power demand data to the EMIS, which comprise real-time loads, forecasted load profiles, and historical load profiles. These data are vital to balance power generation and demand. Technical databases linked to the EMIS from the demand side provide information regarding the consumers' micro-grid and smart home grid topologies (Privat, 2012), sensitized objects, and electrical appliances.

4.2 Data warehouse management layer

The data warehouse management layer is responsible for the processes of extracting, transferring, and loading (ETL) data from the source system layer. Furthermore, data is enriched with additional information to eventually being fed into the decision support layer.

In general, the ETL process links to heterogeneous data sources, which urges for standardized data formats (e.g. XML), the verification of data quality, and the definition of adequate interfaces (Teuteberg and Marx Gómez, 2010). This is especially true for an EMIS designed for the energy sector, as in smart grid environments "the absence of […] universally accepted interfaces, messaging and control protocols, and standards" combined with "ever-changing technologies in communications, IT, and power systems" (Farhangi, 2010, p. 25, 27) poses special challenges to interface design and data exchange of connected components and assets. Here, recent developments of common information models (e.g. IEC 61970) may facilitate the integration of heterogeneous data into the EMIS and could improve data consistency.

This layer also contains a metadata repository, which provides structural information concerning the heterogeneous data that are integrated from the various data sources. Furthermore, policies and regulatory requirements are a vital part of an EMIS (Teuteberg and Marx Gómez, 2010). Here, for instance, thresholds for noxious substances, limits to pollutant emissions (e.g. CO_2, SO_2, NO_x), and priority feed-in regulations for renewable energies complement the data. Generally, this information represents constraints for the superordinate decision support layer. The sustainability assessment framework is unique to the concept of an EMIS, as it "supports capturing data for reporting business performance on sustainability measures" (Ahmed and Sundaram, 2007, p. 3). Such a framework provides logics to aggregate the poly-structured data to compute sustainability indicators. For instance, the various emitted pollutants are converted to CO_2 equivalent to determine the overall environmental burden of power generation and energy distribution for the atmosphere. Ahmed and Sundaram (2007) present a generic sustainability framework that could be applied for the purpose of the presented EMIS. The event engine aims at reacting to unforeseen changes of state. This includes, for instance, triggering self-healing capabilities of the grid by focusing on restoring electricity supply in case of a fault event, e.g. short circuits (Bésanger et al., 2012).

The interface to the superordinate decision support layer is designed by means of an online analytical processing (OLAP) service and, thus, represents a central component of this layer. It converges data provided by the upstream source systems, enriches them with additional information (e.g. legal conditions, sustainability indicators), and prepares them in the required granularity for feeding in the decision support layer. The OLAP service supports instant information flows to all actors and, thus, instant real-time energy management.

4.3 Decision support layer

Energy management, as any other form of management activity, needs decision-making. Therefore, the decision support layer is located at the top of the proposed IT-architecture. The connection to the data warehouse management layer is achieved by standardized data formats (e.g. XML, CSV). The decision support layer aims at giving software-aided, automated real-time decision support to corporate actors, namely the energy supplier who is the system operator, by means of well-acknowledged tools for optimization (e.g. CPLEX), simulation for reliability assessments (e.g. Plant Simulation), and statistical analysis that, for instance, is used for load forecasts (e.g. R).

The energy supplier has a multi-criteria objective function to incorporate both economic (e.g. cost minimization) and environmental goals (e.g. emission minimization) as usual in the context of sustainable decision-making that considers multiple dimensions by nature (Quariguasi Frota Neto et al., 2008). The objectives must be carefully weighed against each other. All data which is necessary to execute the multi-criteria optimization is provided by the data warehouse management layer of the EMIS. The decisions that result from the optimization procedures are subsequently transferred to the entities of the energy supplier to manage the provision of power by adjusting electricity generation and flows. Furthermore, economic and environmental information that result from these decisions (e.g. energy prices and CO_2 emissions) are communicated to the consumers on the demand side. This way, decision-support is also provided to them, as they are able to decide on individual energy demands on that basis, either manually, or within local optimization procedures, or by setting decision rules within their sensitized objects in smart home grids (Palensky and Dietrich, 2011; Privat, 2012). The information sharing is supposed to induce a behavioral change compared to a case where no data is provided, as it enables consumers to follow their individual preferences regarding both economic and environmental aspects of energy consumption and to align them with their convenient demand patterns.

Energy suppliers seek to meet standards for environmental management, such as ISO 14001 certification and the European Eco-management and Audit System (EMAS) (El-Gayar and Fritz, 2006), and are increasingly forced to create sustainability reports in the context of stakeholder information and legal compliance (Teuteberg and Marx Gómez, 2010). This is also supported by the EMIS, as it provides a module to create reports concerning environmental key performance indicators, based on data provided by the sustainability assessment framework located on the subordinate layer.

5 Demonstration of EMIS

We demonstrate the value of the proposed EMIS within an evaluation setting that is partly based on real-world data derived from secondary sources (e.g. scientific knowledge base, public databases) and construct scenarios around the artifact. We select this descriptive design evaluation method to demonstrate the utility of the designed artifact (Hevner et al., 2004).

5.1 Problem description

Following the conceptual model, in the focal setting an EMIS is assumed to work at the interface of an energy supplier, who operates the EMIS to manage the production and transmission of electrical energy, and a network of consumers, who demand electrical energy. This setting requires periodic decision-making of both acting stakeholder groups. In line with Figure 1, decisions of suppliers concern feed-in of energy sources and related plant control, flow network control, balancing energy supply and demand, and energy pricing. In our case the supplier relies on centralized and structured decision-making by means of EMIS-integrated optimization (e.g. CPLEX). On the demand side, consumers mainly decide upon their individual, period-specific energy consumption. In contrast to the supplier, consumers, respectively their sensitized objects, are decentralized by nature and follow individual decision and optimization rules. For this purpose, smart metering systems or energy controllers are installed, which "switch[…] off equipment, based on certain priorities and other rules" (Palensky and Dietrich, 2011, p. 383). Their configuration reflects the individual preferences of each consumer. For the purpose of this demonstration, we model two distinct consumer segments: One group is more sensitive to economic factors, namely energy prices (price-elastic behavior), and the other group is more sensitive to environmental factors, namely CO_2 emissions (emission-elastic behavior). Such a distinction of consumers into 'economic' and 'green' segments is common in other research fields, e.g. in the remarketing of remanufactured products (Atasu et al., 2008). Within our modeled setting, each group comprises 500 fictitious households.

Energy prices as well as CO_2 emissions are a direct result of the underlying energy mix. Electrical energy is generated by conventional coal plants (base loads), conventional combustion turbines fired with natural gas (medium and peak loads), and photovoltaics as renewable energy source. Electricity generated by the latter is hardly controllable as it is mostly determined by solar irradiance. For the purpose of this demonstration, we take irradiation data from Wang and Nehrir (2008). Each energy source shows specific levelized costs of electricity and CO_2 emissions (see Table 1), which ultimately result in electricity prices and emissions depending on the selected energy mix.

Energy source	Levelized cost of electricity [$ / kWh]	CO_2 emissions [g CO_2 eq / kWh]
Conv. coal	0.0956	1,001
Conv. combustion turbine	0.1284	469
Photovoltaics	0.1186	46

Table 1. Source-specific cost and CO_2 emissions, data base on U.S. Energy Information Administration (2014) and Moomaw et al. (2011).

In the next subsection, we conduct an analysis computing three scenarios each covering a day in one-hour periods. Every period, scenario-dependent EMIS information is communicated to the consumers, who decide about their segment-specific energy demand on that basis. These demand patterns are looped back to the system operator, who selects the optimal energy mix by minimizing his scenario-specific objective function, which in turn results in next-period's electricity prices and CO_2 emissions. While the size of the distinct consumer segments is equal in each scenario, significant differences relate to transferred information by means of the EMIS, underlying consumers' decision rules and, thus, resulting energy demand patterns (see Figure 3).

In general, decision rules reflect both consumers' price and emission elasticities of electricity demand (Allcott, 2011; Kirschen, 2003). While the general effect of providing information on demand shifting is documented (e.g. Corbett, 2011), determining the exact trade-off between consumers' convenient demand patterns and prices/emissions is quite difficult. As a result, to the best of our knowledge, generalizable results regarding these elasticities do not exist. For our demonstration case we choose an approach consisting of stepwise elasticities around average values. In this context, decision rules, which control individual electricity demand, are initially defined within the consumers' sensitized objects. These rules consist of both current and average prices and emissions, decision coefficients, and parameters for shifting demands. Current prices and emissions are a result of optimization procedures, while average prices and emissions are computed based on historical data. Both information is generated by components of the top decision support layer of the EMIS and is communicated to the consumers periodically. Decision coefficients (e.g. `0.95, 0.98`, etc.; see Figure 3) are set based on the relative standard deviation of prices ($\sigma_p/\mu_p = 3.6\%$) and emissions per kWh ($\sigma_e/\mu_e = 31.5\%$) in a case where no information is shared. We select decision coefficients symmetrically around the related relative standard deviation for both the economic consumer segment ($0.95 * a < (1 - \sigma_p/\mu_p) * a < 0.98 * a < a < 1.02 * a < (1 + \sigma_p/\mu_p) * a < 1.05 * a$) and the green consumer segment ($0.6 * b < (1 - \sigma_e/\mu_e) * b < 0.8 * b < b < 1.2 * b < (1 + \sigma_e/\mu_e) * b < 1.4 * b$). To set the parameters regarding shiftable demand (e.g. (`0.25 * currentShiftableDemand`); see Figure 3), we first determine the non-shiftable base-demand of a household, which equals the absolute minimum of hourly consumption. We estimate this value to be 80 Wh based on Paatero and Lund (2006). The difference between the actual hourly demand and this base-demand is assumed to be potentially shiftable, but only a part of this is, at least to some extent, realistically shiftable as it stems from the use of washing machines, laundry dryers, and dish washers. These appliances represent shiftable loads (De Ridder et al., 2009), as their rescheduling is more convenient than shifting the use of other electrical appliances, such as lighting, freezers, and entertainment devices. Following Paatero and Lund (2006), the share of shiftable appliances in a household accounts up to 30-40%. According to this, the selected parameters of shiftable demand ensure that a maximum of roughly 38% of hourly demand is shifted.

Within *Scenario I*, the EMIS communicates economic data to the supplier while it neither provides information about electricity prices nor about CO_2 emissions to consumers. Thus, they will follow a predetermined 'convenient' demand pattern in line with Paatero and Lund (2006). In *Scenario II*, real-time prices of electricity are communicated and price-elastic users will either shift a part of their future convenient energy demand to the current period (if the price is below the average/default price) or shift a part of the current period's energy demand to future periods (if the price is above the average/default price). In *Scenario III*, additional information regarding CO_2 emissions is provided to all actors, which induces the supplier to set a multi-criteria objective function. Furthermore, environmentally-sensitive consumers will now reduce energy demands in periods of high emissions, and instead move to periods of low emissions and vice versa. Figure 3 gives an overview about the scenario configurations, including the scenario-dependent objective function of the supplier and the underlying decision rules of the consumer segments in pseudo-code for each period.

Scenario I – Economic information are provided to supplier, no information are provided to consumers

Objective function supplier:
$min((specificCost_s + transmissionCost_s) \cdot generatedElectricity_s);$ $s \in Sources$

Decision rules for both consumer segments:
Follow convenient demand pattern (resulting relative standard deviations: $\sigma_p/\mu_p = 3.6\%$; $\sigma_e/\mu_e = 31.5\%$)

Scenario II – Economic information are provided to supplier and consumers

Objective function supplier:
$min((specificCost_s + transmissionCost_s) \cdot generatedElectricity_s);$ $s \in Sources$

Decision rules for economic consumer segment:

```
Starting point each day is convenient demand pattern
p = current price, a = average/default price
If    (p <= 0.95 * a) Then shift (1/(50 - 2 * currentPeriod)) of remaining daily demand to current period
ElseIf(p <= 0.98 * a) Then shift (1/(100 - 4 * currentPeriod)) of remaining daily demand to current period
ElseIf(p <= 1.02 * a) Then do nothing
ElseIf(p <= 1.05 * a) Then shift (0.25 * currentShiftableDemand) to remaining periods, distribute evenly
ElseIf(p >  1.05 * a) Then shift (0.50 * currentShiftableDemand) to remaining periods, distribute evenly
```

Decision rules for green consumer segment:
Follow convenient demand pattern

Scenario III – Economic and environmental information are provided to supplier and consumers

Objective function supplier:
$min[\alpha \cdot ((specificCost_s + transmissionCost_s) \cdot generatedElectricity_s) + \beta \cdot (specificEmission_s \cdot generatedElectricity_s)];$
$s \in Sources;\ \alpha, \beta \triangleq weighting\ factors$

Decision rules for economic consumer segment:
Same as in Scenario II

Decision rules for green consumer segment:

```
Starting point each day is convenient demand pattern
e = current emissions/kWh, b = average/default emissions/kWh
If    (e <= 0.6 * b) Then shift (1/(50 - 2 * currentPeriod)) of remaining daily demand to current period
ElseIf(e <= 0.8 * b) Then shift (1/(100 - 4 * currentPeriod)) of remaining daily demand to current period
ElseIf(e <= 1.2 * b) Then do nothing
ElseIf e <= 1.4 * b) Then shift (0.25 * currentShiftableDemand) to remaining periods, distribute evenly
ElseIf(e >  1.4 * b) Then shift (0.50 * currentShiftableDemand) to remaining periods, distribute evenly
```

Figure 3. Scenario configurations including objective functions and decision rules.

5.2 Results of scenario analysis and discussion

The time-shifting of demands is an essential part of fostering sustainability in the energy sector (Corbett, 2011). In the context of the demonstration case, we could exemplify how the developed EMIS may induce a shifting of demands through providing behavior-changing economic and environmental information to the energy supplier and the consumers. Along the scenarios, we observe a change of consumption patterns, which increasingly converge towards the non-adjustable supply curve consisting of energy provided by base load plants and renewable energy systems (see Figure 4). On the one hand, the energy difference between the scenario-specific demand curve and the supply curve must be provided by adjustable medium and peak load plants (e.g. the energy difference between curve "Scenario III Demand" and curve "Non-adjustable Supply" between 00:00 and 10:00). On the other hand, all surpluses regarding renewable energies are lost as no energy storages are modeled (e.g. the energy surplus as the difference between curve "Non-adjustable Supply" and curve "Scenario III Demand" between 10:00 and 14:00). Hence, the more the curves match, the better is the balancing of power supply and demand. Against this background, we observe that information-sharing by means of the EMIS significantly improves the alignment of power supply and demand (see Figure 4).

We discuss the evaluation's results (see Table 2) and their interpretation in detail in the following. First and not surprisingly, due to the fact that no impact on energy conservation behavior is modeled, the overall energy demand is constant at 4,973 kWh within each scenario. Nevertheless, all other indicators differ significantly.

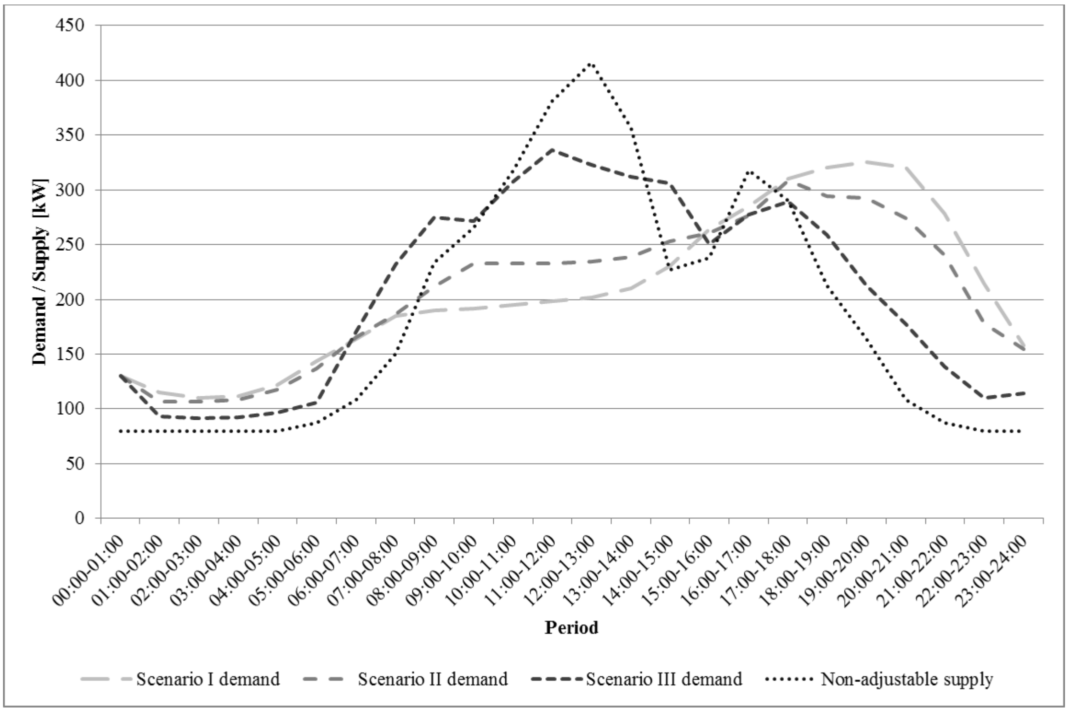

Figure 4. Scenario-dependent energy demand patterns and non-adjustable supply curve.

The share of energy demand that is met by renewable energy increases along the three scenarios from 1,783 kWh to 2,366 kWh (+32.70%). Hence, using the EMIS leads to a better integration of renewable energy sources in the context of the demonstration case. At the same time, the share of electricity demand that is satisfied by burning fossil fuels decreases from 3,190 kWh to 2,607 kWh (−18.28%). Thus, the EMIS is also successful in reducing the use of fossil fuels. Regarding energy efficiency, we refer to the continuously decreasing losses of renewable energies owing to an improved balancing of energy supply and demand, which in turn increases the quotient of constant energy consumption and energy expenditure and, thus, energy efficiency. In terms of economic and ecological efficiency positive results are observable, as overall costs and CO_2 emissions necessary to provide the same utility decrease along the three scenarios (−1.02% respectively –9.47%). The detailed results of the scenario analysis are also illustrated in Table 2.

Indicator	Scen. I	Scen. II	Scen. III	Best Case Scenario
Overall energy demand [kWh]	4,973	4,973	4,973	4,973
Demand met by renewable energy [kWh] (Share of overall demand [%])	1,783 (35.85)	1,971 (39.63)	2,366 (47.58)	2,600 (52.28)
Overall surplus of (lost) renewable energy [kWh]	817	630	234	0
Demand met by burning fossil fuels [kWh] (Share of overall demand [%])	3,190 (64.15)	3,002 (60.37)	2,607 (52.42)	2,373 (47.72)
Overall CO_2 emissions [kg]	2,599	2,520	2,353	2,254
Overall costs for electricity [$]	558.08	556.25	552.37	550.07

Table 2. Results of scenario analysis.

Finally, we compare the set of scenarios against a best case, in which all actors make optimal decisions regarding economic and environmental criteria. Hence, power supply and demand are matched in a way that leads to an optimal solution in terms of lowest realizable costs and CO_2 emissions at given weighting factors α and β for both target criteria in the supplier's objective function (see Figure 3). We point out that along the scenarios all investigated indicators converge towards the respective optimal solution of the *Best Case Scenario*. Analogously, especially *Scenario III*, which exploits the full functionality of the EMIS, shows good results (see Table 2).

Summing up, the demonstration case shows that the EMIS has the potential to fulfill its intended purpose and particularly achieves the objectives set within *Step 2* of the research methodology. We were able to give first evidence about the practical utility of this designed artifact.

6 Conclusion

The present article develops an EMIS that provides economic and environmental data to actors in the energy sector. On the basis of that information, environmental-oriented decisions are fostered, which ultimately lead to an improved balancing of power supply and demand and to more sustainable energy systems. This approach applies the promising integration of energy and IS research by means of EI and responds to the necessity of incorporating environmental aspects into both corporate and consumer decision-making. Overall, we could answer the research question by means of the EMIS.

Within our evaluation setting, we demonstrated how decision-making based on information provided by the proposed EMIS fosters environmental sustainability. It improves the integration of renewable energy sources, reduces usage of fossil fuels, and increases energy efficiency through a better balancing of energy supply and demand. This is achieved by realizing the full possibilities of multi-directional communication of information in smart grids by means of a tailored, central IS. In this context, the EMIS flanks existing EMS and continuously exchanges economic and environmental information with both the supply and demand side. This induces behavioral changes: On the one hand, the EMIS systematically integrates environmental data and constraints into a corporate IS, which enables the energy supplier to perform structured environmentally-oriented decision-making by means of a multi-criteria objective function. On the other hand, providing not only economic information but also environmental information to consumers of electrical energy creates incentives for eco-conscious consumers to shift energy demands to periods of low CO_2 emissions, as the lack of such information often prevents people from such a more sustainable behavior (Watson et al., 2012).

Nevertheless, the present article leaves room for further research. Although our evaluation setting uses realistic data, we could only give first evidence of the practical utility of the proposed EMIS. We suggest implementing the EMIS in comprehensive field studies in collaboration with suppliers of electrical energy, for example to analyze the cost structure of such a system and to quantify the trade-off between costly information-sharing and economic benefits (Feuerriegel et al., 2013). In addition, we did not model possible reductions of total electricity consumption that could result from a shift of demands within our demonstration case. As previous research indicates that energy conservation is feasible in such settings (Allcott, 2011), their consideration could further increase the value provided by the developed EMIS and, thus, represents a promising area for future research. This could also be true for the incorporation of energy storages, in particular for the inclusion of decentralized energy storage devices. In this context, taking into account emerging networks of electric vehicles seems to be promising (Brown et al., 2010). Furthermore, we generally imply a positive effect of providing environmental information on consumers' behavior in terms of time-shifting demands. This assumption is in line with prior research (Watson et al., 2012), although the actual degree of influence and related elasticities are rather unknown. Hence, we suggest examining this interdependence empirically within field studies. As a last promising research field we emphasize the growing importance of cloud-based data in smart grids (Privat, 2012). This opens up a considerable pool of accessible data and could enable large-scale usage of the developed EMIS.

To sum up, the EMIS seems to be suitable to foster environmental-oriented decision-making in the energy sector. It achieves the stated objectives and fulfills important functions that constitute "an integrated system for an energy system" as it "ties together the various elements to provide a complete solution" (Watson et al., 2010, p. 27). Nevertheless, much work still has to be done to transform the energy sector into a sustainable business. We believe that the developed EMIS represents a small building block to sensitize suppliers and consumers of electrical energy to consider environmental dimensions in their decision-making processes.

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