Contributions to the advancement of Decision Systems in Energy Informatics

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Abstract

Energy Informatics (EI) as a subfield of Information Systems (IS) has received much attention during the past decade due to its relevance and ambition in closing information gaps that if left open would prevent actions in favor of climate protection. The source of such actions are decisions and decisions, in turn, are the outcome of decision-making processes. Yet, decision-making in the energy domain remains unsatisfying. This is mainly because the energy consumption problem of humanity continues to be far from solved.

In that regard, EI's perspective is that the right information, at the right place, at the right time, in the right quality will motivate sustainable behaviors, culminating in the often-cited formula "*Energy + Information < Energy*". With this premise, Decision Systems (DS) supporting well-grounded decisions in information-intensive processes are a particularly important type of IS to EI. Therefore, the contributions of DS have very high relevance to advancing EI. Designing, evaluating, and communicating DS in EI, however, requires considering their purpose, their architecture, their stakeholders, and the development of the field.

To that end, this cumulative doctoral thesis aims at characterizing DS' potential in EI and accumulating respective design knowledge through a holistic, conceptual view on the intersection of EI and DS as well as through tangible exemplars of research. All exemplars of research are solution-oriented and have a distinct environmental focus seeking to respond to senior scholars' calls for more IS research of this type. This thesis comes with four attached research articles. Each of them addresses a specific research question through an evaluated design artifact. All articles are classified according to the conceptual view developed in this thesis. The analysis and comparison of literature along the conceptual viewpoints have uncovered the potential for research to turn more toward unstructured and wicked problems as well as lifecycle stages beyond the planning and operation phases. This thesis demonstrates that DS can leverage several decades of experience and knowledge to tackle these areas in EI methodically and systematically from now.

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I. Introduction

I.1 Motivation

In 1977, Nobel Prize laureate Herbert Simon wrote in the *Science* magazine article *"What Computers Mean for Man and Society"* that "[e]nergy and information are the two basic currencies of organic and social systems. A new technology that alters the terms on which one or the other of these is available to a system can work on it the most profound changes" (Simon 1977b). From today's point of view, we may see this notion as a premonition to what Watson et al. (2010) three decades later termed *"Energy Informatics"* (EI)[1], namely and metaphorically speaking: "*Energy* + *Information* < *Energy*". By this notion, Simon, as a thought leader in the decision sciences, foretells the profound potential of (information) technology to improve the efficient and effective use of both energy[2] and information[3]. He acknowledges that both are essential input factors to any society and therefore drive prosperity. Specifically, energy use, and in particular the use of electricity reveals a strong and causal relationship to economic development, e.g., quantified by the gross domestic product (Ayres and Warr 2010). This relationship strongly reflects major societal transformations.

The energy demand of pre-industrial societies was comparatively low. Humans mainly used wood for heating and cooking. During industrialization, energy became an important input factor as the invention of the internal combustion engine increased labor productivity and output. These new technologies initiated the transformation from an agricultural society to an industrial society. Liquids-based energy carriers such as oil only accelerated this development also fueling low-cost, long-distance, rapid transport and thus globalization (Solé et al. 2018). However, only electricity enabled computer-based information processing and thus gradually transformed an industrialized society into an information society (Webster 2002). The transformation from an agricultural society to an industrialized society and then to an information

[1] "Energy informatics is concerned with analyzing, designing, and implementing systems to increase the efficiency of energy demand and supply systems." Watson et al. (2010).

[2] Energy is the potential to do (mechanical) work.

[3] As working definition, information can be construed as the resolution of uncertainty.

society is at its core characterized by energy and its use. Over time, technological innovations have radically changed the way energy is supplied and consumed. And in turn, the changes in the way that energy is supplied and consumed define what we today refer to as energy transitions. Radical changes in the way energy is supplied and consumed happened multiple times in human history. And, so did energy transitions, as well. The carriers of energy, e.g., wood, coal, and oil, characterized previous energy transitions. In the past, economic forces drove these transitions, i.e., the stakeholders experienced economic benefits shifting from, e.g., wood to coal. Yet, we observe a different type of energy transition taking place today. This time economic forces did not initiate the transition to renewable sources of energy (RES) for a growing number of end-uses in first place. Instead, the current energy transition originated from an academic debate, which first centered on the finiteness of resources (Meadows 1972) and later shifted to climate change as a human-made phenomenon (Höök and Tang 2013). Both streams of the debate, however, emphasized the role of non-internalized external costs, i.e., a single or group of natural or juridical entities burdens another group of natural or juridical entities by performing some action without compensating for the caused damage (Hardin 2009). In the case of climate change, external costs relate to all damage caused to the public by greenhouse gases (GHG) emitted into the atmosphere, e.g., from burning fossil fuels. These damages stem from - but are not limited to - increased risks of drought, floods, extreme humid heat, rising sea levels, etc. The fundamental view of the academic debate is that internalizing external costs should lead to the economic viability of RES. This debate continued in politics manifested by the United Nations (UN) Framework Convention on Climate Change in New York, in 1992 (United Nations 1992), followed by the Kyoto Protocol in 1997 (United Nations 1997), and lastly by the UN's Paris agreement (United Nations 2015). Referring to the Kyoto Protocol, the German government initiated its plan for a national energy transition – the so-called "Energiewende".

Decarbonization is at the heart of the current energy transition on both the national and international levels. Decarbonization means to reduce, avoid, capture, and use GHG in the energy supply chain (provision, conversion, delivery, and use). Environmental economists measure the progress of decarbonization of an economy in terms of emission intensity, i.e., the GHG (in grams carbon dioxide equivalents) per kilowatt-hour of energy. To that end and since practically all economic activities are based on the use of energy, the current energy transition transforms the economy into a low-carbon one. In this respect, the input factor "information" gains further relevance.

Most of the economies' productivity gains of the last 30 years have resulted from information (goods or services), whereas in the 19th and 20th-century energy use was the dominant productivity driver (Ayres and Warr 2010). Since then, technological progress of energy (conversion) efficiency has been slowing down as it reaches physical limits. Yet, there remain considerable inefficiencies regarding the end-uses of energy (Watson et al. 2010), i.e., the utility that humans receive from an energy service could be met with less energy in the right form, at the right place, at the right time[4]. This view on efficient use of energy, of course, evades a definition based on physical laws but takes a socio-economic viewpoint. To that end, in a hypothetically perfect world, each actor or decision-maker (a human, a group of humans, a legal entity, a regulator, etc.) would carry out actions and processes, which use the input factor energy in a utility-maximizing way. Apparently, this perfect world does not exist. In this regard, Watson et al. (2010) hypothesize that decision-makers lack information and, hence, solution-oriented information systems (IS) research can and ought to contribute to improving decision-making (Klör 2016). While IS have been known to largely contribute to productivity increases in the last half-century through solution-oriented information technology (IT) artifacts including implementations, e.g., Dedrick et al. (2003) and Stiroh (2002), IS' impact on environmental goals yet appears to remain behind pledges, wishes, and repetitive calls by senior scholars (Melville 2010; Seidel et al. 2017). In this vein, Gholami et al (2016) argue that "IS research leadership should take a stance towards addressing climate change". However, Gholami et al. (2016) - who extended a study of Malhorta (2013), analyzing almost 30 IS papers published since 2008, found that only Corbett et al. (2013) and Loock et al. (2013) contributed to the "design" and "impact" stages of the research process. In contrast, this thesis aims at contributing to the "design" stage through all its attached research articles (RAs).

Thus, in this thesis and "[i]n line with an information biased Weltanschauung, [I] take an IS focus to addressing global warming and creating a sustainable society [and I] see

[4] Likewise, given an energy-service constituted by its form, place, and time, it holds that there potentially is an end-use and a human (or a group of humans) drawing higher utility.

the problem as a lack of information to enable and motivate economic and behaviorally driven solutions” (Watson et al. 2010). As the overall objective, EI research strives to deploy information and communication technology (ICT) to support the transition to sustainable economies (Goebel et al. 2014) by collecting and analyzing energy datasets to support the optimization of energy distribution and consumption networks (Watson et al. 2010). As outlined in Watson et al. (2010), EI stimulates IS research to address environmental sustainability from an energy perspective because of the sectors’ detrimental and predominant contribution to global warming. However, “EI research can only inform the design of these systems sufficiently if economic considerations are part of their evaluation and if the proposed solutions take existing institutional frameworks, e.g., current electricity market designs, into account“ (Goebel et al. 2014). For this particular reason, all presented RAs in this thesis are designed in accordance with regulatory and institutional frameworks (e.g., market design, national/local regulation, etc.) while the potential for generality has always been pointed out. Regarding generality, Watson et al. (2018) highlight that the “Energy Informatics framework [...] has been applied to multiple domains, such as road pricing, farming, logistics, bicycle sharing, and others.” There, it sets out to ultimately drive sustainable actions.

When sustainable actions are the ultimate goal of EI-related contributions, informed decision-making is a pre-requisite. Informed decision-making in turn is driven by information and insights (Sivarajah et al. 2017). Decision problems in EI research are oftentimes not only very intricate but also expose high degrees of variety. Therefore, many EI contributions are designs on Decision Systems (DS) or Decision Support Systems(DSS)[5] (Goebel et al. 2014). DS are prominent socio-technical artifacts in design-oriented IS research (Gregor and Hevner 2013). They have been applied to support diverse operational and analytical tasks in many domains, e.g., sustainable investments (Khalili-Damghani and Sadi-Nezhad 2013), water resource management (Mysiak et al. 2005), sustainable supply chain management (Wu and Pagell 2011), and healthcare (Musen et al. 2014). According to Klör (2016), they can address all types of decision problems. Since research on DS dates back to the early 1970s, the field has

[5] As introduced in more detail in chapter III, the more general term is decision system. In the remainder of the text, the abbreviation DS is used consistently also when it refers to the specific subclass of decision support systems.

built vast design knowledge (Hevner et al. 2004). Applying this knowledge to EI challenges, however, requires understanding the problem context, identifying the related DS concepts, choosing the appropriate design options, and eventually bringing them into application. Brendel et al. (2018) consider similar challenges for designing artifacts in Green IS, which contains EI as a subfield (Watson et al. 2010). To that end, research studying the application of methodologies within a domain or a field help (other) researchers classify their research, sharpen their contribution's positioning, and identify research gaps within or outside of the identified classification (Brendel et al. 2018). This is relevant to Green IS research and thus to EI research. Research and interest in the field of EI are continuing and perhaps gaining momentum as underlined by recent calls for papers in dedicated issues in leading IS journals (Staudt et al. 2019). DS have had an important impact on this emerging field (Klör 2016). Turning to the massive challenges climate change is about to bring, it is not far-fetched suggesting that DS will continue to represent relevant and meaningful contributions to the field of EI research in future. This is because they are known to support decision-makers in finding effective and efficient solutions, which are urgently needed in all relevant contexts and sectors of today's and future economic system. In addition, they support decision-makers in overcoming humans' innate cognitive biases in various decision-making settings.

I.2 Research aims, contribution, and structure of the thesis

As asserted by Simon (1977b) energy and information are basic currencies of organic and social systems and drivers of economic development and human prosperity. While technological progress fosters energy efficiency (Nemet 2006; Weiss et al. 2008), recent developments cannot overcompensate the human demand for energy. Therefore, much attention has been paid to the input factor information. To that end, DS play a decisive role. In this cumulative doctoral thesis, I, therefore, strive to contribute both by individual essays and by framing and capturing the design of DS in EI in a holistic way. Recent publications in the area of design-oriented IS research in Green IS (Brendel et al. 2018) and DS research in Green IS (Farkas and Matolay 2022; Klör 2016) lay a basis for this thesis but do yet not incorporate the intricacies that come with EI research. The thesis also addresses a broader audience than the individual essays, which all are specific but very diverse instances of DS in EI. While this thesis lays its focus on DS in EI, there are contributions in EI and D(S)S that do not match the scope of this thesis. E.g., purely empirical research in EI unrelated to supporting decision-making or systems for decision-making outside of the scope of EI. However, my motivation is to contribute to the existent body of knowledge with this thesis in the following ways:

- **Solution-orientation.** This thesis may be construed as a response to calls for more solution-oriented IS research to be impactful (Malhotra et al. 2013; vom Brocke et al. 2012; Watson et al. 2010).
- **Environmental focus.** Likewise, this thesis responds to on-going calls by senior IS scholars to contribute to environmental problems in general, and climate change in specific (Gholami et al. 2016; Seidel et al. 2017; Staudt et al. 2019).
- **DS' potential in EI.** The thesis sets out to highlight the relevance and potential of DS to tackle environmental problems in general and climate change in specific.
- **Design knowledge.** To facilitate design knowledge for research at the intersection of DS and EI, this thesis aims at characterizing the intersection in a structured and systematic way.
- **Tangible exemplars.** Lastly, this thesis strives to contribute with tangible exemplars of research that capture several characteristics along the identified dimensions of DS in EI.

As to address those research aims, I structure this cumulative doctoral thesis as follows: Chapter II summarizes the focal concepts from Energy Informatics and their Energy Informatics Framework (EIF) by Watson et al. (2010), which also graphically presents relevant components of solution-oriented EI. Besides, I add the concepts emerging from its application to support design knowledge. Thereafter, chapter III introduces the focal concepts from DS. Both chapter II and chapter III seek to provide design knowledge. Chapter IV summarizes the identified dimensions from both DS and EI before it characterizes the four RAs attached in the appendix as instances of DS in EI. As tangible exemplars, I present them along the dimensions from DS and EI as outlined in chapters II and III. Chapter IV, thus, classifies my research contributions based on a structured approach following the dimensions that are introduced in the chapters before.

Eventually, chapter VI concludes this thesis by summarizing the key findings from the previous chapters before identifying limitations and giving an outlook on future research. My individual contributions to the RAs of this doctoral thesis are described in the appendix. Figure 1 presents the structure of the thesis visually as a summary.

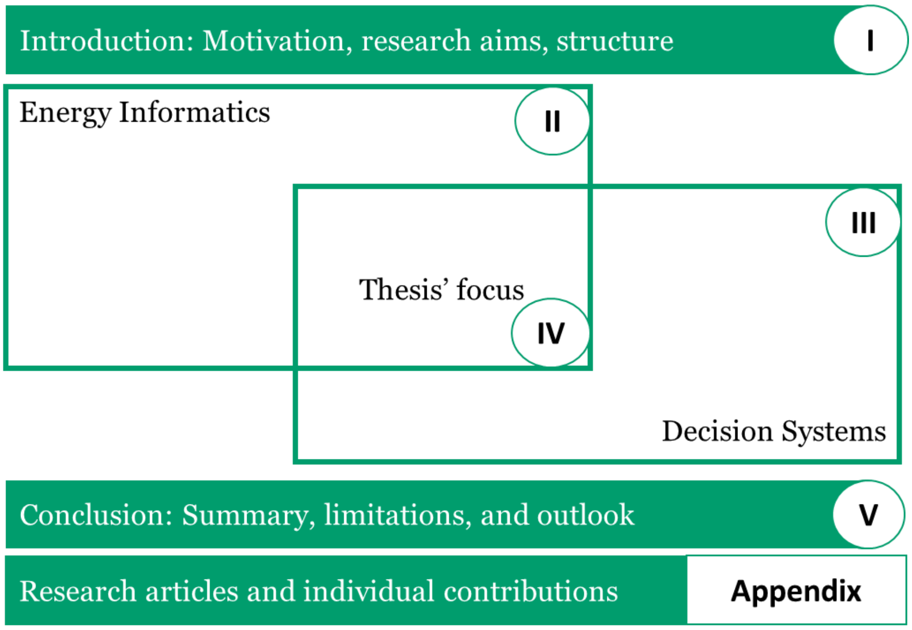

Figure 1 The thesis structure consists of five chapters and an appendix encompassing abstracts from four research articles as well as a further publications subsection.

II. Energy Informatics

Based on established search engines and bibliographic databases for scientific articles, namely, WebESCO, Web of science, AIS, ACM, IEEE Explore, Scopus, and Google scholar, I reviewed the history of the term "Energy Informatics". The first mentioning of "Energy Informatics" leads to Sachau (2003), a German researcher, who presents a distribution method for acquiring electricity offers and demand. However, Sachau has yet never defined what he considers "Energy Informatics" to be. Leucker and Sachenbacher (2009) at Technical University of Munich (TUM) are forerunners of the notion "Energy Informatics" as well. However, the view by Leuckner and Sachenbauer (2009) on "Energy Informatics" applies a purely technical lens positioning it at the crossroads of engineering and computer science. In this thesis, I take – as mentioned in the introduction section – the canonical view by Watson et al. (2010).

Given the research by Sachau (2003) as well as Leucker and Sachenbacher (2009), Watson and his co-authors (2010) may not have been the first to introduce the term to the scientific community but they were the first to formulate the idea “energy + information < energy”. This idea also dates back to a panel discussion at the Americas Conference on Information Systems (AMCIS) back in 2009. In 2010, Watson et al. (2010) clarified what they conceived „Energy Informatics“ to mean. In particular, it also stresses its social dimension by including stakeholder behaviors. In addition, they laid out an EI framework (EIF). The framework maps the relationships among the EI concepts. In the following, when I refer to the EIF I limit the descriptions to the necessary minimum while referring the reader to the relevant literature for more detail. In addition to the original EIF, updated versions, extensions, and related work have surfaced in academic literature, which all help better shape the field. For that reason, I take them into account for a comprehensive view on EI. Eventually, I refer to concepts pertinent to all EI solutions as invariants. These invariants may have multiple characteristics, which then all apply to the EI solutions. I refer to concepts that are not invariants as dimensions. All these dimensions have mutually exclusive characteristics (within the same dimension), e.g., for the dimension “Solution approach” the applicable can *either* be “Optimizing” *or* “Satisficing” but not "Optimizing” *and* "Satisficing” at the same time. In contrast, for the invariant “stakeholders” in EI *all* three characteristics are *always applicable at the same time*. I present the concepts and their characteristics within the sections II.1-II.7 and III.1-III.6.

The EIF itself brings in four important concepts, namely, the stakeholders (cf. section II.1), the goals EI adheres to (cf. section II.2), the forces that bring about change (cf. section II.3), and the energy system technologies on both the supply and consumption side (cf. section II.4). In addition, to the EIF, Klör (2016) highlights the importance of considering the stages of the lifecycle of an energy system. This is because IS solutions typically target a dedicated lifecycle stage. I present the characteristics of the lifecycle stage dimension in section II.5. Also, IS solutions also serve dedicated functions in these lifecycle stages. The function refers to the degree of involvement in the course of events (from exclusively passive to explicitly active functions). I adopt a classification of characteristics based on Braun and Strauss (2008). Eventually, in section II.7, I elaborate on the accounting level of an energy system, i.e., at what level to measure the quantities of energy involved. Despite not being part of the original EIF, its designers have presented multiple case studies (Watson and Boudreau 2011), where this dimension has been stressed from different levels. For this reason, and in line with research in energy systems analysis and energy economics (Pfenninger et al. 2014), I outline its characteristics in appropriate detail.

II.1 Stakeholders

As with any sociotechnical system in general and IS in specific, the EIF considers stakeholders as important components for system change (Savaget et al. 2019). While in theory there are various conceivable groups of stakeholders (Freeman 2010), the EIF considers three major groups, namely, governments, suppliers, and consumers. Watson et al. (2010) consider these stakeholders as critical to any energy system, but acknowledge that subgroups may be relevant from case to case, e.g., local governments in contrast to state governments. In this thesis, I associate all stakeholder subgroups with governments, suppliers, and consumers. These groups are sufficiently specific while they continue to be of indispensable genericity. This allows individual pieces of research to easily map specific stakeholders to these generic groups. In the following, I summarize the groups of stakeholders as proposed by Watson et al. (2010).

Governments. In general, governments can be construed as a human system governing an organization. An organization often is a state, which again may be composed of constituting entities. While in the Western World, these governments will often be elected leaders, in many parts of the world autocratic leaders constitute governments. In addition, governments exist on national and local levels. To that end, Williams (1961) characterizes archetypical local governmental structures, which shape governmental stakeholder types. Osborne (1993) considers principles of governing styles on a national level. These types and styles help researchers conduct research in the field of EI. As Watson et al. (2010) point out the stakeholder groups "suppliers" and "consumers" (as I introduce in more detail hereafter) "do not always create outcomes that are in society's long-term interests" (Watson et al. 2010), e.g., externalizing environmental costs such as air pollution. Thus, governments use public policy instruments to influence social, technical, and economic change. Their key tools are threefold: carrots, sticks, and sermons (Bemelmans-Videc et al. 1998). This metaphorical typology refers to steering change by economic means (carrots), by regulation (sticks), and by information provision (sermons). In democratic states, non-governmental stakeholder groups exert influence on governmental decisions by voting and direct involvement such as petitions, public hearings, and complaint filings. Using public hearings as a citizen sounding board is a widely used instrument for environmental impact assessment (Glasson et al. 2013). To that end, public hearings are also discussed in RA4 as part of the electricity retail rate design.

Suppliers. In the EIF suppliers are entities (either organizations or individuals) that provide energy and/or energy services. Organizations providing energy services are typically private companies but may also be state-owned businesses. The latter happens to be the case even in countries subscribing to market economies because some parts of the energy supply chains feature monopolistic characteristics. In particular, this holds for very capital-intensive infrastructures, e.g. an electricity network. Also, individuals can be suppliers, e.g., by feeding an electricity network with power from a photovoltaic rooftop panel. These individuals are then referred to as active (utility) customers (Abdelmotteleb et al. 2018), prosumers (Toffler and Alvin 1980), or more recently also prosumagers (Sioshansi 2019). Suppliers are regulated and receive supervision by governmental organizations. For example, in RA4 I compare a novel ratemaking method against the prevalent ratemaking and the rate structures in place. Irrespective of whether a supplier is a single individual or a large corporation, according to Watson et al. (2010), all strive for increased effectiveness and efficiency (cf. section II.2).

Consumers. This group of stakeholders is the ultimate reason why there are energy systems including all other stakeholder groups. Without consumers, there was no demand for energy and energy services and thus, no need for suppliers would exist. Without suppliers (and consumers), there was no need for policy instruments regarding energy (services). That dependency puts the stakeholder group ‘consumers’ in a position of power. Consumer behavior and its malleability is therefore a focal point of EI research (Goebel et al. 2014; Loock et al. 2013). As mentioned, this is only emphasized by the fact that energy is an important input factor to any economic system and the foundation for much of today’s prosperity of modern societies. Similar to suppliers, consumers can be all individuals, businesses, or also governmental organizations. They may have different service requirements but generally adhere to similar principles and goals as suppliers which I shall therefore expand on jointly in section II.2

II.2 Goals

As to understand the intention of EI and its mission, it is recommendable to both look at the seminal essay by Watson et al. (2010) and the research notes expanding on the then-new field by Goebel et al. (2014). The latter interprets the field from a business & information systems engineering (BISE) perspective, which slightly extends the original views as I discuss in the following.

Watson et al. (2010) suggest that EI's goals are directed toward averting global warming (as pars-pro-toto for climate change) in first place, while the EI goals are more generally hinged toward (environmental) sustainability as the overarching concept: "[…] we take an IS focus to solving global warming and creating a sustainable society […]" (Watson et al. 2010). More particularly, Watson et al. (2010) propose EI as a new subfield of IS "that recognizes the role that IS can play in reducing energy consumption, and thus CO_2 emissions". In this way, the authors see the detrimental effects of the energy sector on climate change as pivotal and the focal point of research efforts. However, as they also hinge toward the more general goal of creating a sustainable society, Watson et al. (2010) also add in a less often cited footnote that the EIF equally applies to other scarce resources, e.g. water. As mentioned before, in this doctoral thesis, I put a focus on energy rather than arbitrary resources as a matter of scope and coherence. The intention by Watson et al. (2010) culminates in the widely recognized (metaphoric) inequality "energy + information < energy". This inequality, however, sets a focus on consumption as is expressed by the statement that the authors "[…] see the problem as a lack of information to enable and motivate economic and behaviorally driven solutions." (Watson et al. 2010).

This being recognized as a blind-eye, Goebel et al. (2014) add "renewable energy supply" as an equivalently oriented goal toward addressing climate change. EI takes an IS lens on solving climate change rather than an engineering perspective. Adding renewable energy supply as a goal might thus appear to have EI leaning toward engineering solutions. To that end, it is important to see that renewable supply is largely determined by practically uncontrollable weather events. When supply is highly volatile and stochastic, demand needs enhanced flexibility (Schöpf 2020; Thimmel 2019). While this does not necessarily require consumers to reduce consumption, it asks them to shift demand. In line with the original intention by Watson et al. (2010), missing flexibility can be construed as a lack of information by the stakeholders, as well. Thus, IS solutions can motivate and enable beneficiary behavior. Research that addresses the goal of enhancing flexibility allows for (more) renewable supply and hence lower emissions. Therefore, such research aligns well with the scope and aims of EI.

These two perspectives, namely "reducing energy consumption" und „increasing flexibility (renewable energy supply)" to reduce emissions have a perfect fit with the abstract goals identified by the sustainability literature and which are presented in the EIF, i.e., eco-efficiency, eco-effectiveness, and eco-equity (cf. Dyllick and Hockerts 2002). Therefore, in this thesis, I propose the three aforementioned goals as invariants.

Eco-efficiency. According to DeSimone and Popoff (2000), **"**eco-efficiency is reached by the delivery of competitively-priced goods and services that satisfy human needs and bring a quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's carrying capacity". To that end, energy-efficiency is a special case of eco-efficiency. As indicated before, the definition of energy-efficiency in specific and eco-efficiency, in general, evades a definition purely based on physics. A prominent example of this is the consideration of the occupancy of a building (or room) via digital sensors, which reduces energy consumption without improving physical efficiency. In essence, eco-efficiency is a socio-economic measure of resource efficiency. Therefore, it evades the otherwise purely physical definition and requires considering measures such as the utility of stakeholders. In this vein, Halbrügge et al. (2020) present a solution for an electric vehicle (EV) charging park with limited power capacity (e.g., either one relating to physical power capacity or also an economic one), where the authors target an eco-efficient power allocation through utilitarian welfare optimization.

Eco-effectiveness. The concept of eco-effectiveness as introduced by Braungart McDonough (1998) reflects the ideas proposed by Goebel et al. (2014) to not only increase energy-efficiency but also to facilitate human (economic) activities through renewable energy supply or even avoid consumption completely. This view aligns well with Peter Drucker's management mantra "doing the right things rather than doing the things right" as claimed by Braungart and McDonough (1998). For example, in smart districts city planners will design district layouts such that travel journeys will be short or even unnecessary rather than focus on more eco-efficient vehicles. To do so planners will need various types of information and its constituent data. In this regard, EI research has vast potential to contribute by stressing eco-effectiveness. Since such innovation will be highly contextual, i.e., specific to the locality, bottom-up innovation processes for digital solutions help exploit previously unidentified potentials. Hosseini et al. (2018) present a notable contribution to how villages or small communities can create IS-based, bottom-up innovation processes.

Eco-equity. Some solutions may be either eco-efficient or eco-effective on a local level, temporal level, or for specific human groups but may fail to be so in a global or universal way. Those solutions are hardly equitable ones. Therefore, Gray and Bebbington (2000) have introduced the concept of eco-equity. As an example, a lignite-fired power plant equipped with carbon capture and storage technology will only be eco-equitable, if the GHG captured and stored can be contained eternally. Otherwise, the current generation receives the benefits from the energy but burdens future generations with the emissions without compensation. It remains to be seen whether our legacy is inclusive of solutions entirely designed to address eco-equity.

Summarizing, EI solutions should address the three eco-goals, namely, eco-efficiency, eco-effectiveness, and eco-equity. These overarching eco-goals are generic enough so that they broadly comply with (environmental) sustainability (i.e., they are concerned with arbitrary (scarce) resources). Instances for energy-specific goals can be easily derived by substituting resources with energy and GHG, respectively (Goebel et al. 2014).

II.3 Drivers of change

EI solutions and their potential to achieve the eco-goals as discussed before will be dependent on what Watson et al. (2010) refer to as external forces, which drive the change. The literature distinguishes between three kinds of forces: “policies & regulations”, “economics”, and “norms” (Watson and Boudreau 2011). In section II.1, I presented three major groups of stakeholders, who determine how these external forces are put into practice and how they affect the settings, in which an EI solution resides. Therefore, drivers of change are not part of an EI solution but the EI solution is part of a setting characterized by the external forces. In the following, I introduce these three types of external forces individually in some more depth since “EI research can only inform the design [...] in a satisfactory way if economic considerations are part of their evaluation and if the proposed solutions take existing institutional frameworks

[...] into account" (Goebel et al. 2014)

Policies & regulations. A major force determining the institutional frameworks and settings, in which an EI solution operates, are the policies of the governmental stakeholder group. In the present case, policy instruments are government interventions designed to bring about change in favor of one or another (eco-)goal. Policymakers rely on the policy instruments I introduced in section II.1, namely, carrots, sticks, and sermons. Information-based interventions (sermons) are the least intensive. Economics-based interventions (carrots) are more direct and intense. Finally, direct regulation-based interventions (sticks) are the most binding since they enforce practices and conducts. Policy instruments have both steering and distributional effects that need to be taken into account. Steering effects describe increased or decreased demand on an absolute level because of interventions. Distributional effects describe re-allocations among groups of natural or juridical entities. The assessment should at best take place before an instrument becomes effective, e.g., via IS-based simulations of the regulation (Kahn 1995).

Economics. In addition to policymaking, economic forces are an essential driver of change. This is the more eminent the more market-oriented a country operates. While in economies with a social planner regulation might be the key force, in capitalist economies, the key force might be economic efficiency. The economic force has at least the following underlying three pillars. First, eco-efficient solutions consume less energy and generally have lower operating expenses. Second, the cost of financing might be lower through green bonds (Zerbib 2019). Third, stakeholders might be willing to pay a premium for sustainable products and services (Ha-Brookshire and Norum 2011).

Norms. Next to economic forces and policy instruments, norms affect both supplier and consumer stakeholder groups. There are generic types of norms, namely, personal and social norms. While the latter exist on a group level in firms and private groups (e.g., friends, family, etc.), the former work on an individual level. According to Schwartz (1977) and Stern et al. (1999) personal norms are beliefs by an individual about how s/he is supposed to behave. The perceived opportunity of rewards and the perceived threat of sanctions influence an individual's actions. In this thesis, the loci of focus rest on economic and policy-based forces. Literature is vast on their inter-relations, e.g., Steg et al. (2005) who consider the influence of personal norms on the acceptance of energy policies; or Rekola and Pouta (2001) who find that personal norms play a decisive role in an individual's willingness to pay for environmental protection. In contrast to personal norms, social norms are based on perceived group expectations rather than self-expectation for the opportunity of rewards and the threat of sanctions. Social norms thus are effective by social pressure (Thøgersen 2006), which also may be perceived differently among the individuals within a group. To summarize, both types of norms are a force of conformance concerning expectations formed by values and beliefs (Stern et al. 1999).

II.4 Energy system technologies in demand and supply sides

While according to Watson et al. (2010), EI solutions should always strive for an integrated demand and supply energy system, exemplars of research demonstrate a greater breadth of contributions. On the one hand, some studies solely focus on one side of an energy supply system. On the other hand, in more recent times, research tends to extend the EIF by simultaneously considering multiple energy systems, e.g., considering electricity and gas at the same time. This breadth is reflected in what the EIF terms energy system technologies. Energy systems technologies serve as the technical building blocks of the EIF. As mentioned, research does not always explicitly model all the energy system technologies. However, the explicitly modeled energy system technologies help classify and comprehend individual EI contributions quickly. From what is modeled, we see four scopes of EI, i.e., levels of abstraction. In the following, I, therefore, present the four scopes of EI contributions, namely, demand, supply, integrated demand and supply, and multi-energy-systems-centered ones.

Demand. Frequently, EI researchers study the demand-side in isolation or model the demand-side explicitly. This, of course, can be interpreted as an immediate consequence of the main goal of EI research, i.e., to reduce energy consumption by utilizing information. This information commonly refers to consumption data. As with all data, such applications are subject to data quality challenges. As a practical example, RA2 identifies time intervals for the measurement of power that are superior from an economic point of view. This challenge is addressed by studying and contributing to solutions regarding sensitized objects (Watson et al. 2010):

Sensitized object. Since the first energy transition, most human activities use energy other than mechanical work by humans and animals. However, only recently digital technology can sense energy/demand usage patterns, e.g., quantity, time, and location. Collecting data for measurement is the first and necessary step toward understanding demand. A comprehensive understanding of the demand drivers is a precondition to influence demand in terms of predefined goals, e.g., the aforementioned eco-goals. Sensitized objects as considered by Watson et al. (2010) provide such functionalities and, thereby, provide the basis for novel energy-saving services. Well-studied examples are simple user feedback mechanisms, e.g., Loock et al. (2013) or Bitomsky et al. (2020). Besides, sensitized objects also enable new business models, e.g. for energy-savings contracting solutions (Töppel and Tränkler 2019). Eventually, objects can receive sensitization retrofits that equip vintage objects with digital technology to empower solutions. Considering the economic viability of such retrofits is important to EI solutions geared toward the investment and planning phases of an energy systems lifecycle phase (cf. II.5).

Supply

The same applies to the supply side as to the demand side. Only (computerized) measurement of the supply side's state allows for managing the system. In contrast to the demand side, the supply side by definition also encompasses the transmission and distribution to the demand side (Watson et al. 2010). This requires EI contributions focusing on the supply side to consider network structures. The EIF models two types of these structures, namely, flow networks and sensor networks, which I both introduce as energy system technologies in the following.

Flow network. "A flow network is a set of connected transport components that supports the movement of continuous matter (e.g., electricity, oil, air, and water) or discrete objects (e.g., cars, packages, containers, and people)" (Watson et al. 2010). By this definition, it becomes clear that a flow network forms a set of actuators that perform actions in the physical world. As a note, a flow network may or may not be grid-bound, i.e., there are flow networks that have no fixed geospatial position. Flow networks for liquefied natural gas on large ships serve as such an example. Theoretic optimization (i.e., algorithms) of flow networks is subject to research since the origins of operations research (e.g., Domschke 2015). However, in reality, the optimization of flow networks turns out as an information-intensive endeavor. Humans are incapable of handling such massive amounts of data. For that reason, a second network has been established representing the digital twin of the flow network.

Sensor network. “A sensor network is a set of spatially distributed devices that reports the status of a physical item or environmental condition” (Watson et al. 2010). In general, as a digital twin of the flow network sensor networks collect and provide data on as many objects in a flow network as necessary for the management of an energy supply system. It is still an open research question at what granularity in time, at which locations, and at what accuracy data collection of flow network is optimal. To that end, RA2 contributes to this research question and related ones for an electricity distribution network operator (DNO) regarding the cost of matching demand and supply.

Integrated demand and supply

As by its original intention, EI sets out to not only focus on either side of an energy system but to effectively and efficiently connect both sides by an IS (Watson and Boudreau 2011). The IS can have various functions in an EI contribution as I outline in section II.6. Irrespective of the function of an IS in an energy system, an integrated energy system and corresponding research will ex- or implicitly refer to all energy system technologies from both demand and supply sides to achieve the eco-goals: sensitized objects, sensor networks, flow networks. Integrated analyses are often a prerequisite to electricity-based energy systems as power needs to be consumed in the very instant it is generated. Not surprisingly, much of EI research thus addresses the electricity system (Kossahl et al. 2012).

Multi-energy systems

Recent studies have highlighted the positive synergies of coupling energy systems (Brown et al. 2018; van Nuffel et al. 2018), e.g., the natural gas network with the power network (Power-to-Gas) or a district heating system with power generation facilities. This has let an extension of the original EIF become popular (Huang et al. 2017). The extension of the EIF acknowledges that in real-world energy applications, there are other nodes than those for consumption and supply. Namely, there are storage nodes, which can work either as a consumption node or as a supply node in an energy system. The difficulty was also highlighted earlier by Brandt et al. (2014) already. However, Huang et al. (2017) also added a hitherto completely new type of node to the EIF, i.e., conversion nodes. Like the concept of storage nodes that either work as a consumption or as a supply node, conversion nodes work as a consumption node in one energy system and as a supply node in another energy system. For example, in Power-to-Gas applications two integrated energy systems connect. First, the electricity-based energy system and second, the gas-based energy system. A conversion node, e.g., an electrolyzer uses electric power to split water molecules (H_20) into hydrogen (H_2) and oxygen (O_2). Hydrogen is a gas that then can be used in many gas-based end-use applications. Thus, such a conversion node consumes power in the electricity-based energy system (consumption node) but adds supplies to the gas-based energy system (supply node). In EI research, there are first contributions following up on that concept, e.g., the EI-based DS by Golla et al. (2020) that aims to support the scalability of citizen energy communities for electricity, mobility, and heat.

II.5 Lifecycle stages of the energy system

As described in the previous section II.4, EI research will need to consider energy system technologies that together constitute the energy system. Energy systems do not simply start to exist and simply perish thereafter. Instead, energy systems are emergent and evolving systems. Lifecycles of energy systems span 40 and more years (Harrison et al. 2010). IS scholars have proposed to design solutions along an energy system’s lifecycle. In a larger Green IS context, Melville (2010) considers lifecycle phases mainly for goods. Klör (2016) adopts and adapts Melville’s classification of lifecycle stages to study DS contributions in the field of Green IS. Similarly to Klör (2016), in this thesis, I apply Melville’s classification to contributions in the field of EI, as well. In particular, the four considered stages within a lifecycle of an energy system are planning and investment, operation, repurposing, and disposal, which I introduce in the following.

Planning and investment. Before an energy system including its constituting technologies (cf. II.4) is built and put in place, EI contributions support the design and planning activities (e.g., RA3, RA4, Brandt et al. 2014). Planners can have multiple goals in mind when designing energy systems. However, when considering the various groups of stakeholders (e.g., RA6, Fridgen et al. 2015a), economic goals are essential (Lehtveer et al. 2015; McCollum et al. 2018) since much of early planning activities are directed toward economic viability rather than technical feasibility, which comes as a second step, only (Gamarra and Guerrero 2015). Similar to the RAs attached to this thesis, many important EI contributions targeting this stage of an energy system’s lifecycle are DS (Brandt et al. 2014; Fridgen et al. 2015a; Golla et al. 2020).

Operation. The planning and investment stage is concerned with the design of energy system technologies as considered in section II.4, e.g., flow networks, sensor networks, and sensitized objects. The operation stage is then concerned with the operation of the designed energy system technologies. This holds in particular for the IS of energy systems. Concerning the operation of an energy system, e.g., in electric mobility, or building energy systems, IS receive much attention in the scientific literature (Kirpes et al. 2019; Xu et al. 2018). While EI contributions targeting the planning and investment stage oftentimes also model operational activities, EI contributions targeting the operation stage need to take the contextual characteristics of any specific energy system into account, e.g., standards regarding smart meter data management (Jagstaidt et al. 2011) or the general data protection regulation (General Data Protection Regulation 2016). In addition to standards and protocols, user interface design may decide on the success of an EI contribution (Xu et al. 2018). Often there is a (near) real-time requirement for these types of IS as well (Bitomsky et al. 2020).

Repurpose. After an operational period, all systems approach the end of their current use. Either they are dismantled and disposed or they are repurposed[6]. The latter contributes to either eco-effectiveness or eco-efficiency. It leads to eco-effectiveness when an energy system can be used in a different context beyond its planned lifetime. It leads to eco-efficiency when an energy system needs to be retrofitted, refurbished, or recycled such that it (or parts of it) can be reused by adding fewer resources than were necessary when built from scratch. To that end, many EI contributions to date focus on the repurposing of used batteries from electric vehicles (Bräuer et al. 2016; Klör et al. 2018; Monhof et al. 2015). However, some yet unexplored application fields are conceivable for EI contributions, e.g., solar panels that are no longer eligible for the fixed grid feed-in remuneration (in Germany after 20 years). Research from related disciplines studied, e.g., repurposing buildings (Assefa and Ambler 2017) and repurposing existing internet-of-things infrastructure on campus to promote energy-saving behavior (Bates and Friday 2017).

Disposal. Eventually, at the ultimate end of any energy system, it will be disposed of. To date to the best of my knowledge, there is no EI contribution particularly stressing this stage of the lifecycle. However, solutions regarding nuclear waste from nuclear power plants are an open question for example. Identifying storage locations and

[6] In this thesis, I conceive the term reuse to be a special case of the more general concept of repurposing.

managing their security is an unsolved quest. EI solutions could potentially contribute to that area or help avoid generating nuclear waste in first place.

II.6 Functions of Information Systems in Energy Informatics

At the heart of every EI contribution, there is an IS as prescribed by the EIF and recognized by notable exemplars of EI research (Brandt et al. 2014; Fridgen et al. 2015a; Fridgen et al. 2016). According to Watson and Boudreau (2011), an IS ties together the supply and demand as well as the components of an energy system. In line with Braun and Strauss (2008), an IS can create information ties, incentive ties, and control ties. Note that these ties remotely reflect the three types of policy instruments as discussed in section II.3. By establishing these ties, an IS may serve various functions, namely, information (provision), incentives (and remuneration), incentive-based direct control, and direct control (Braun and Strauss 2008). In the following, I introduce the four IS functions and their behavior in interactions with their users (decision-makers). For details regarding the specific tasks IS perform in the field of EI, I advise the reader to consult Watson et al. (2010) as well as Watson and Boudreau (2011).

Information. Most IS in the field of EI provide information to users (and decision-makers in the case of DS) to trigger decisions that lead to actions, which on their account contribute to the eco-goals subject to the requirements and constraints applicable to the IS of the energy system under consideration (e.g., RA3, Bitomsky et al. 2020; Loock et al. 2013). This IS function might be most native to EI's intention of utilizing information to reduce energy use. Types of the provided information can be either the condition of the system such that the user acts upon this information (e.g., energy consumption) or more directed information on recommend actions, e.g., shifting energy consumption to times when prices are low (Fridgen et al. 2016). Much of the information provision is based on data and analytical methods, which I present in more depth in section III.6. These types of IS tend to be Decision Support Systems in their classical interpretation, i.e., supporting a decision-maker with information so that better decisions are made. Especially EI contributions addressing lifecycle stages other than the operation stage subscribe to this IS function.

Incentives. In addition to information provision, some IS provide incentives to motivate actions in desired directions. Incentives may be monetary as well as non-monetary. An example of a monetary incentive coordinated by an IS is real-time pricing of power tariffs for retail customers (Fridgen et al. 2018). Other contributions extend their focus beyond sole information provision by appealing to humans' cognitive biases (e.g, Agha-Hossein et al. 2015). IS employing digital nudges (e.g., Tiefenbeck et al. 2018) typically fall into this category of non-monetary incentives. In any case, acting upon incentive-based IS remains voluntary to the IS' users.

Direct control. When an IS assumes the function of exerting direct control either on the supply-side, the demand-side, or both, the IS does not only provide information to its users and/or decision-makers but also acts on their behalf. This comes with the caveat that these IS require bi-directional communication capabilities (Braun and Strauss 2008), which may not be a commonality in the highly regulated energy sector (Jagstaidt et al. 2011). Many EI contributions utilizing this type of IS function like RA2 are also automated DS addressing the lifecycle stage 'operation'. Direct control is oftentimes a means to lower transaction and coordination costs at the expense of potentially higher fixed costs for the initial IT setup (Malone et al. 1987).

Incentive-based direct control. IS incorporating the function of incentive-based direct control combine traits of both direct control and incentive-based IS. EI solutions featuring incentive-based direct control ask users to conditionally allow direct control. As long as the condition is not met, the IS does not have the right to control sensitized objects, flow networks, etc. However, if the condition is met, the IS can do so. In order to have an IS user or decision-maker commit to such a policy, an IS must provide incentives similar to those described above. One such example is the trade of options for interruptible electricity loads by mid- and large-sized consumption units (Horowitz and Woo 2006).

II.7 Energy accounting level

As outlined before, EI is concerned with achieving the goals as presented in II.2. Those goals are generic and relevant. However, the goals need to be adapted to the respective study because generic goals are not all of the following at the same time: specific, measurable, achievable, and time-bounded. These criteria for goal setting are attributed to the concept of "management by objectives" by Peter Drucker (1954) and were later laid out as a canonical concept by Doran (1981). To that end, energy accounting is an instrument to make EI's goals effective by tying up strategic goals and actionable objectives in line with guidelines by Doran (1981). To make objectives specific, researchers and practitioners in EI need to specify the perspective they take when studying energy systems, i.e., setting the energy accounting level, which may be one of the following, on which I elaborate hereafter: energy end-uses, energy carriers, or objects: As to date, there is no generally accepted classification of energy sectors and their more specific end-uses, e.g. water heating, such that the sectors do not overlap and are exhaustive at the same time. The International Energy Agency (IEA), the statistics bureau of the European Commission (Eurostat), and the IPCC are relevant authorities taking a classification approach. Some studies also choose to define their viewpoint individually, e.g., Schäfer (2005) describes a sectoral model by economic sectors in line with Fisher (1939). He adds "residential" and splits services into transport and others. Pérez-Lombard et al. (2008) acknowledge that prior research oftentimes follows the "Industry, Transport, Other (Residential, Services, Agriculture)" classification while arguing – in line with the IEA (2019) that buildings deserve their perspective. It is a consensus that sectoral perspectives are an important energy accounting level and thus similarly represent a valid choice when conducting EI research. In this thesis, I follow IEA's definition because of its global and widely trusted perspective. At the same time, I shall not argue that assuming the classification by IEA is the only rightful one. However, it will suffice as a working classification and may be corroborated in future by other researchers studying DS in EI. For energy carriers, a diverse set of definitions is available. However, in contrast to the end-uses and sectors, the common elements are broader. As a working definition, in this thesis, I use the IPCC classification outlined below. Lastly, objects consuming energy are innumerable but serve as the most disaggregated level of energy accounting. Particularly since objects are gradually more often sensitized, this unit of analysis becomes feasible and effective for EI contributions. In the following, I briefly, touch each of the energy accounting levels considered in this thesis.

End-uses and energy (end-use) sectors

Energy sector. The energy sector is a GHG emitting sector covering the generation from primary energy sources, conversion, transport, distribution, and end-use of energy. It accounts for nearly 90% of global CO_2 emissions and represents the primary contributor to climate change (IEA 2019). For a comprehensive account of the energy sector and its supply chain, I refer to the IPCC report on climate change

(Intergovernmental Panel on Climate Change 2015). Often the focus of studies, however, rests on the end-uses of energy, only. Then, researchers and analysts bundle all generation, transport (including distribution), and conversion activities into what they term “the energy sector”. As a result, energy end-uses become separated from the rest in IEA’s definition of the energy sector and its supply chain. Specific end-uses (e.g., water heating) are aggregated into end-use sectors. The classical end-use sectors are buildings, industry, and transport.

Buildings. The end-use sector “Buildings” accounts for 40% of total energy use in the EU (European Parliament and of the Council 2010). Germany has the EU’s largest building stock (European Commission 2015). Its residential buildings are responsible for 22% of the countries’ total energy use (German Federal Ministry for Economic Affairs and Energy 2018). Buildings consume various energy services as end-uses. For example, in Germany, thermal energy for heating and hot water determines 84% of the total energy use in residential buildings (German Federal Ministry for Economic Affairs and Energy 2018). Generally, the composition of a building’s total energy use varies widely across geographies. For example, in some parts of California, buildings use little thermal energy due to their moderate climate but a majority for electrical appliances.

Industry. According to the U.S. Energy Information Administration, “the industrial sector uses more delivered energy than any other end-use sector, consuming about 54% of the world’s total delivered energy”[7] (Conti et al. 2016). In line with the same report, the industrial sector is divided into the subsectors energy-intensive, non-energy-intensive manufacturing, and non-manufacturing industries. For a detailed tabular grouping, I refer the reader to Conti et al. (2016). Depending on the subsector, operating entities use energy for purposes such as processing and assembly, steam and cogeneration as well as process heating and cooling. In particular, the consortial research project “SynErgie” studies these energy uses for their potential to apply demand side management (Buhl et al. 2019). In that project context, Schöpf (2020), studies EI’s potential to contribute to both short- and long-term demand-side flexibility in industrial contexts.

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[7] Delivered energy is measured as the heat content of energy at the site of use according to Conti et al. (2016)

Transport. The transport sector comprises the passenger subsector and the freight subsector. The worldwide passenger subsector accounts for 61% while the freight subsector accounts for the remaining 39% of total transport energy use according to the U.S. Energy Information Administration (Conti et al. 2016). Transport modes in either sector include cars, trucks, buses, 2- and 3-wheel vehicles, trains, aircraft, and marine vessels. For a detailed sectoral analysis, I refer the reader to Conti et al. (2016) for an international perspective and to Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (2018) for a detailed analysis of the German transport sector. Both internationally and in Germany, the transport sector is largely fueled by non-renewable energies as the combustion engine preserves its dominant status in this sector for now. However, recently much effort is put into electrification – either battery-based or by fuel-cells. Unsurprisingly, EI's focus stresses information needs, especially regarding battery-based electric vehicles (e.g., Fridgen et al. 2014; Halbrügge et al. 2020; Haupt et al. 2020). EI research on fuel-cell-based electric vehicles remains niche to date (Kleiner et al. 2017).

Energy carrier types

Next to end-uses and end-use sectors, energy carriers offer a different and valuable perspective on measuring and accounting for energy. While end-uses do not focus on how the energy is provisioned for the end-use, energy carriers make a distinction to that end. Accounting by energy carrier types, however, does not acknowledge how the energy is put to application. For this reason, they are a helpful energy accounting system for intermediate steps in the energy supply chain, e.g., as demonstrated in RA2. Energy carrier types describe the form by which energy is transported and delivered. To that end, all end-use sectors can make use of any type of energy carrier as represented in Figure 2. Classical energy carriers can be solids, liquids, and gases. As mentioned before, formerly, most of the energy was based on wood and coal (solid) and then turned to oil (liquid). Only more recently, (natural) gas has become an important pillar of the energy system. In addition, electricity (e.g., directly generated by photovoltaics panels) can be an energy carrier. All these energy carriers require a different infrastructure (i.e., a different type of flow network) and are therefore often a unit of analysis to EI research.

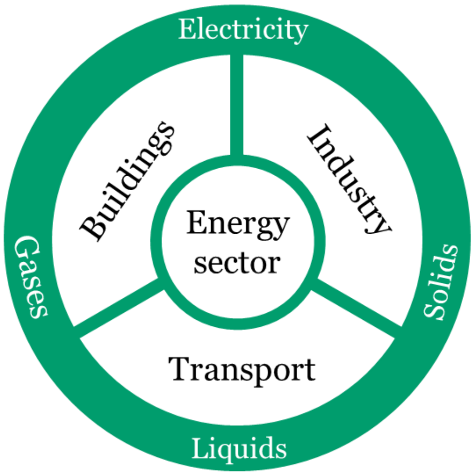

Figure 2 Energy carriers interfacing with the energy-use sectors, which combined encompass the energy sector.

Objects' energy use over their lifecycle

Eventually, on a more granular level, energy accounting approaches in EI oftentimes study the energy use of singular objects, e.g., parcels, cargo containers, or passenger cars, etc. (Watson and Boudreau 2011). This approach is considered especially relevant for lifecycle assessments (cradle-to-cradle), i.e., the accumulated amount of energy that an object requires over its lifetime. Lifecycle assessments are prevalent for many energy-intensive objects like heating, air conditioning, and ventilation (buildings) but also concerning vehicle types (transport) (Bauer et al. 2015), or cans based on industrial aluminum (industry) (Niero and Olsen 2016). Thus, EI researchers might choose to perform evaluations based on the accounting of single objects.

In summary, EI is a growing field of research at the interface of multiple disciplines including IS/BISE, computer science, energy economics/policy, and technology. The seminal work by Watson et al. (2010) described the EIF and inspired EI research. This thesis gathered extensions and related contributions as dimensions that classify contributions that subscribe to the field. In that vein, Huang et al. (2017) added the concept of integrated and multi-energy systems to EI. A lifecycle dimension originates from research by Melville (2010) and was extended by Klör (2016). According to Watson et. al. (2010), an IS rests at the core of each EI system. Already before the introduction of the EIF Braun and Strauss (2008) laid the basis for describing the functions of IS. Finally, as to operationalize the eco-goals suggested by the EIF, it is pivotal to consider the dimension 'energy accounting level' to make eco-goals smart in line with requirements postulated by Doran (1981) on goal-setting. These considerations were necessary to fully capture and systematically structure the field of EI of today. Figure 3 visually depicts the extended EIF as used throughout this thesis.

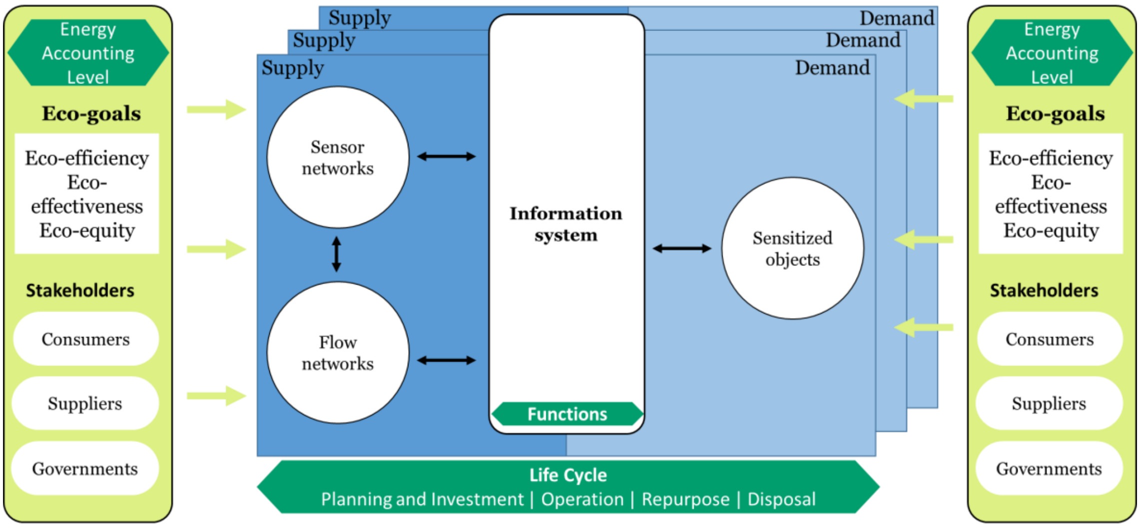

Figure 3 Energy Informatics Framework by Watson et al. (2010) and its extensions as discussed in chapter II.

This extended EIF applies to any solution-oriented EI contribution and hence in particular to DS in EI as I introduce them in chapter III.

III. Decision Systems

According to Klör (2016), decisions are the source of actions. Decisions, in turn, are the outcome of decision-making processes. The concept “decision” is the unit of analysis in the decision sciences, while a DS refers to a socio-technical artifact, which is not only a frequent design target but also a unit of analysis in solution-oriented IS research supporting decision-making processes (Gregor and Hevner 2013). Decision-making in the energy domain in specific and in the environmental sphere in general remains unsatisfying (Gholami et al. 2016). This is mainly because the energy consumption problem of humanity remains far from solved. Therefore, contributions of DS can have very high relevance to EI. Designing, evaluating, and communicating DS in EI, however, requires considering their purpose, their architecture, their stakeholders, and the development of the field. As one of this thesis’ goals is to support research in this field, I lay out the basis of DS in EI. This also requires acknowledging the origins of DS research:

Turning to the past of DS, we see the term "Decision System" coined and used earlier than the term "Decision Support System" with earliest appearances in the 1960s (cf. Cyert and March 2013). According to Power et al. (2019) researchers of the 1960s were proponents of the idea that decisions can be carried out by humans and machines alike. While these statements might coincide with early progress in artificial intelligence and visions of cybernetic systems, later research in the field trended more toward the usage of such systems in managerial contexts (Scott Morton 1971). The major premise in that area was that senior managers use these systems to support experience and gut feeling by evidence. However, researchers were aware that rarely all necessary information was available in machine-readable form. To that end, the term "decision support system" highlighted the purpose of the system. Five decades later, however, digital technologies have drastically changed management decision-making. In many – admittedly – operational workflows, we see computers making decisions not only with consent from humans but autonomously based on empirical evidence and advanced machine learning methods. One very apparent example is autonomous vehicles (Bonnefon et al. 2016). Due to the increasingly autonomous decision-making by computers, Power et al. (2019) encourage researchers to rethink the term "decision support system" and rather use "decision system" as the more general term instead. According to Power et al. (2019), the term DS includes DSS. Therefore, I also use the term DS in this thesis. I present the components of DS in section III.1. The nature and the types of decision problems that these components jointly address are at the core of section III.2. There are links between the types of decision problems and the types of objectives of DS. Therefore, I choose to introduce the types of objectives next in section III.3. Thereafter, I present the solution approaches by DS to address the presented decision problem types and their objectives in section III.4. Some solution approaches are more prevalent among certain types of decision-makers. Therefore, section III.5 presents the four distinct and comprehensive types of decision-makers. Finally, I link the types of objectives and the types of decision-makers to the types of analytical support (analytics types) in section III.6.

III.1 Components of Decision Systems

Based on Sprague (1980) as well as Sprague and Carlson (1982) DS build on the same three generic components, i.e., a dialog, data, and models (DDM). Clearly, in addition to the technology itself, there are three sets of capabilities handling these types of technologies. Users are typically not considered part of the DS but outside the system (Sprague 1980; Watson 2018). While all DS feature these three generic components, it is relevant to mention that scientific research articles tend to stress and focus on either of them in isolation or treat them as an opaque subsystem, i.e., a black box. As research strives to theorize and validate existent theories, looking at too many (design) variables jointly makes research impracticable to conduct and communicate. In the following, we briefly introduce each of the three components.

Dialog. In Sprague (1980)'s seminal work, a dialog connects the user to the DS. Later, Sprague and Carlson (1982) more intuitively termed this subsystem interface. Yet, the term dialog continued to be used by other researchers (Gerlach and Kuo 1990). Interfaces to the DS can be of any type. Typical interfaces are textual, graphical, and more recently also cognitive ones. The latter refers to interfaces that are natural to humans such as spoken language or gestures. In the modern era of computing, interfaces do not need to be human-machine interfaces but can also be machine-machine interfaces as outlined by Turban (2005) already. In addition, modern digital technologies such as robotic process automation use machines working on top of human interfaces (Hofmann et al. 2020).

Data. For DS in specific and IS in general, data represents descriptive knowledge (Dorf 1999). Data describes real-world concepts and phenomena important to be incorporated in decision-making processes. Data comes in various forms, i.e., structured (e.g., numerical spreadsheet data), semi-structured (e.g., web pages), and unstructured (e.g., images), and is stored in databases. In addition to its form, data may have various levels of quality.

Databases. DS store data in a variety of types of databases. The choice of database is not only dependent on the data itself but also subject to technological innovation. In times of high volume, high velocity, and high variety of data, system architectures have considerably evolved when compared to architectures in the early years of DS. More importantly, however, especially DS in research use machine-readable interfaces to query data from external databases, i.e., databases outside the system boundary. As data curation is both time- and labor-intensive, sharing curated databases is a service business model in many application domains (Mayernik et al. 2013; Skourletopoulos et al. 2016; Truong and Dustdar 2009). Watson (2014) gives a full account of modern data architectures and their management.

Data quality (DQ). DQ is an extraordinarily relevant concept as it helps relate data to information (Zins 2007). Many researchers in the field of computer science have defined DQ based on its intrinsic concepts, i.e., independent of "the context in which it is produced and used" (Strong et al. 1997). In settings with human DS users, "this focus on intrinsic DQ problems in stored data fails to solve complex organizational problems" (Strong et al. 1997). Recent approaches to DQ stress a multi-dimensional approach including accessibility DQ (accessibility, access security), contextual DQ (relevancy, value-added, timeliness, completeness, amount of data), and representational DQ (interpretability, ease of understanding, concise representation, consistent representation) in addition to intrinsic DQ (accuracy, objectivity, believability, reputation) in line with Strong et al. (1997). Acknowledging this difficulty, RA2 and RA3 provide relevant examples of how DS can leverage techniques to cope with different levels of data quality and its dimensions by choosing appropriate models.

Models. DS maintain one or potentially arbitrarily many (decision) models in their model base. Models describe algorithmic procedures on how a DS attains its results. To accomplish the results, these models access and use data from the DS database. Among many prevalent model types, two prominent ones are analytical models and machine-learning models.

Analytical models have often their origin in related fields such as operations research and management science (Sprague 1980). Many energy engineering applications follow physical laws which are the basis for analytical models (for building energy cf. Zhao and Magoulès (2012)). To that end, analytical models describe (already well-understood) cause-effect relationships and are thus referred to as white-box models.

In contrast to analytical models, machine-learning models can recognize patterns in data. This allows building models without explicitly modeling cause-effect relationships as these models learn from input data, which may also comprise non-physical measures. Consequently, machine-learning models must be trained (i.e., fitted to the relevant data) before they can be applied in a DS. Yet, machine-learning models come with their own issues. Most prominent is overfitting where machine learning models learn patterns from the data they are trained with that do not generally hold outside of the training data. Besides that, learning pseudo-correlations, i.e., correlations that do not exist because of cause-effect relationships but are merely side-effects, can lead to unsatisfying results.

That is why it is important to apply caution when choosing either model type. Sprague (1980) has already pinpointed the common mistake that simply plugging in a decision model into a DS likely may be considered model misuse. He presents model builders' preoccupancy with the mere structure of the model as a blatant fallacy. It is for this fallacy that model builders often assume the existence and correctness of data input. In this context, RA3 provides insights into this fallacy focusing on energy performance assessments of residential buildings. RA3 reveals the application of steady-state energy quantification methods to be pseudo-accurate. It presents a robust machine-learning-based model as not only more effective but also more efficient. In that example, energy auditors use physics-based analytical models to issue so-called energy performance certificates, which are compulsory for most buildings in the European Union. But while the mathematical calculations are correct, these models are sensitive to inaccurate data input. However, even experts cannot reliably assess some of the very technical input parameters. In contrast, RA3's machine-learning-based model uses simple non-technical data as input, e.g., the class of construction years, which even occupants without training can reliably assess. RA3's authors also present an explanatory model when using the analytical model and when the machine-learning model (Wederhake et al. 2022). This may help future DS builders to decide between different kinds of decision model(s). This decision aid may be construed as a meta-decision model, i.e., a decision model for choosing a decision model on a specific problem. To that end, Sprague and Carlson (1982) suggest embedding such meta-decision models into a model base management system of a DS.

While RA3 presents the selection of a single decision model, many other applications involve model integration. It is also Sprague (1980), who highlights the difficulties of integrating multiple models. From his finding, he states that "models tended to suffer from inadequacy because of the difficulty of developing an integrated model to handle a realistic set of inter-related decisions". According to Sprague (1980), the problem of integrated models lies in the poor communication between individual models that otherwise only deal with distinct parts of the overall problem. In that vein, Ketter et al. (2018) suggest simulation-based approaches and corresponding simulation environments for testing integrated models as testbeds. A prominent example of a pricing mechanism for power retailers is the competitive benchmarking environment

Power Trading Agent Competition (Ketter et al. 2013; Ketter et al. 2016a, 2016b). In RA4, the authors also present a comparably large simulation environment for an energy utility. In that piece of research, the authors encapsulated the model for decision-making by utility customers regarding their investments in distributed energy resources and consumption. This allows researchers and practitioners to also choose other models than the Distributed Energy Resources Customer Adoption Model (DER-CAM) developed and maintained by the Lawrence Berkeley National Laboratory (LBNL) in future (Milan et al. 2015; Stadler et al. 2014).

III.2 Decision problem types

Central to the concept of decision problem types is the concept of the "*decision problem*" itself. First, the use of "decision problem" in computer science, which is related to EI (Goebel et al. 2014), is somewhat different than in decision sciences, which are related to DS. In computer science, a decision problem is defined as a binary decision if a specific sequence of characters (from an allowed list of input characters – the so-called alphabet) exists in a (potentially empty) solution set (the so-called formal language). A classic example is primality. E.g., is 2 in the list of prime numbers? For a formal definition, I refer to Hromkovič (2004, p. 28). While this definition may be useful for complexity theory, in the decision sciences the term problem, to which I adhere in this thesis, may be conceived as a situation where an actor (decision-maker) needs to undertake a decision (i.e., choose a feasible alternative from all possible courses of action) to solve the problem, i.e., resolve the discrepancy from the current state to another (targeted) one. In this vein, researchers in the decision sciences may use the terms "problem" and "decision task" interchangeably (Gerrity 1970, p. 11). For a discussion on problems and their types, I refer to Simon and Newell (1958). As we learn from Gorry and Scott-Morton (1971) based on Simon (1960) decision problems are not a homogenous set but should be further differentiated into subclasses. These subclasses are archetypes in the sense that problems, in reality, might have some traits of another subclass (Simon 1973). Nonetheless, the archetypical character of the subclasses helps classify research. Therefore, in this thesis, I propose and present the following three main groups applicable to the field of EI:

1) well-structured problems,
2) ill-structured problems, and

3) unstructured/wicked problems.

Well-structured problems. According to Simon (1960), many decisions can be "programmed to the extent that they are repetitive and routine, to the extent that a definite procedure has been worked out for handling them so that they don't have to be treated de novo each time they occur". Thus, if it is possible to completely elucidate a decision problem, discover all conceivable decision alternatives, and eventually evaluate each of them before making a choice, then the decision problem under consideration meets the requirements of a completely well-structured problem. Dependencies among the parameters and variables can thus be completely identified and formalized. In practice, however, completely well-structured problems are rare as real-world problems typically exhibit uncertainties and ambiguities. DS addressing this type of problem usually are grounded in methods from operations research and control theory (Pardalos et al. 2011). In scientific practice and applied research, many real-world problems are reduced and abstracted such that they fall into this class. However, contributions making excessive use of assumptions risk providing poor guidance for decision-making and actions. In this vein, many decision problems that are considered well-structured are in fact at least ill-structured (Simon 1973).

Ill-structured problems. In the essay by Simon (1973), a list of criteria is presented that still holds today for what constitutes a well-structured problem. The same list may also serve as a "negative list" to identify problems that evade structuredness to some degree. This implies that all problems that do not fully satisfy those criteria may be considered ill-structured. Among the ill-structured problem type, there happen to exist well-distinguishable subtypes (Pardalos et al. 2011). Two prominent subtypes are also present in the RA attached to this thesis:

First, problems with multiple quantifiable conflicting goals are ill-structured. For example, in RA4, we observe a regulatory authority accepting or revising electricity rate structures. While the contribution by RA4 adds to the structuredness of the decision problem, in the end, all solutions that are Pareto optimal are conceivable alternatives. However, ultimately the regulatory authority has to choose exactly one alternative. Then, choosing a specific alternative defies logical reasoning and only allows it to be governed by (public) opinion, i.e., subjective preference. As stated by Roy (1996), in such cases preference elicitation is an important part of decision-making. This is in addition to identifying the feasible set of actions.

Second, for some problems, it is possible to list all potentially infinite decision alternatives but there is no consistent preference order. RA4's decision problem would fall into that category if it were a diverse set of stakeholder groups that would decide upon rate structures instead of the regulatory authority. In addition, many ill-structured problems feature uncertainties at multiple levels. This also includes uncertainties stemming from the vagueness of the considered objectives. To this end, another facet of uncertainty regarding the objectives is the shift of objectives over time as the environment is usually evolving. This potentially leads to the phenomenon that a decision problem that theoretically can be well-structured appears ill-structured when there is little time.

Unstructured problems/ wicked problems. These types of decision problems rest on the other end of the structuredness spectrum. According to Simon and Newell (1958) not only do such problems exhibit a degree of uncertainty regarding their parameters and interdependencies. It is also hard to identify unambiguous processes for finding solutions. Notable exemplars of this problem type are finding a marketing mix for a solar panel distributor or the design of effective policies for emissions reduction in the building sector. Interestingly, in design-oriented research answering the research question typically constitutes an unstructured problem in itself. However, within the class of unstructured problems, there is a prominent subtype important to present and elaborate on separately. This is because it evades systematic problem-solving approaches, namely wicked problems. In research, wicked problems receive particular attention, as they are mostly very relevant problems to humanity. For this reason, many research disciplines have taken up efforts to particularly address this subtype. According to Rittel and Webber (1973), a wicked problem is a problem for which the formulation of the problem itself represents the problem. As an implication of this definition, a problem formulation is the solution to a wicked problem. Rittel and Webber (1973) contrast wicked problems with "tame" soluble problems in many formal sciences (Rittel and Webber 1973). In formal sciences, objectives, constraints, and corresponding solution spaces are definite. For wicked problems, however, it is unclear how solution candidates can be identified and even less clear is how they should be evaluated. A major difficulty in why a problem turns out as a wicked problem is that multiple problem domains interconnect with one another in a way such that it is impossible to disentangle them by abstraction.

In the IS and BISE disciplines, wicked problems have emerged in parallel. This was driven by Kunz and Rittel (1970) who described elements of IS that are necessary to address such types of problems. Later DeGrace and Stahl (1999) studied wicked problems in the IS development process. Eventually, Watson et al. (2010) recognized the importance of global warming as a wicked problem. He argues that IS researchers should accept their responsibility to contribute with information designs and solutions (Watson et al. 2010). To that end, Ketter et al. (2016b) have suggested an IS-based research methodology, particularly addressing wicked problems. Ketter et al. (2016a) highlight the benefits of big data and analytics to tackle wicked problems in the field of global warming.

III.3 Objectives and parameters

Decision-making does not only differ regarding the type of decision problem but also regarding the types of objectives codifying the goal(s). The most general division of objective types is by their number. Well-structured problems tend to be single-objective problems but need not be. Similarly, unstructured problems tend to expose multiple potentially conflicting objectives, but need not have multiple objectives, as I will demonstrate. This is why it is relevant to DS researchers in the domain of EI that they are aware of a problem's peculiarities before design. In decision analysis, single- and multi-objective decision-making are based on either one but more often on multiple parameters. These parameters form the design space of a problem, where a single instance is referred to as a decision vector. In the following, I shortly present all four conceivable combinations of objectives and parameters adapted from Keeney et al. (2003). Eventually, it is relevant to remark that some decision problems do only have an implicit objective as decision-makers conceive all feasible solutions to be equally satisfactory. However, finding a solution to such problems can be similarly difficult.

Single-objective-single-parameter

The simplest yet frequent combination is the single objective, single parameter problem. The objective and the parameter can be either discrete or continuous. As mentioned, usually this combination of objective/parameter decision problem relates to well-structured problems. One example based on modern portfolio theory is a DS that supports a decision-maker to identify the minimum variance portfolio[8]. However, some single-objective-single-parameter-problems turn out to be widely accepted as unstructured, e.g., the–- admittedly fictive–- problem of finding the perfect point of time (single parameter) to host a party to boost class image for a teenager (single objective). Dependencies among dates are opaque, information on the plans and interests of classmates is scarce, and likely it is uncertain. In addition, the objective is probably too vague as well as too subjective to be formalized. These characteristics point toward an ill-structured problem.

Single-objective-multi-parameter

Many decision problems depend on more than a single parameter. Most single-parameter problems can be disaggregated (i.e., making them less abstract) such that the problem is dependent on multiple parameters. However, in a practical DS, more parameters need not necessarily lead to the best performance. As an example, in RA3, the authors design a DS with few parameters in comparison to a DS designed for expert users and find that the simple (abstract parameters) lead to higher levels of accuracy compared to even experts using another tailored expert DS. Thus, the number of parameters is a relevant property. However, more parameters do not necessarily make the DS more helpful in decision-making.

Multi-objective-single-parameter

Alternatively, some decision problems irrespective of their location on the structuredness spectrum feature multiple objectives. As a special case, some of them only depend on a single parameter, e.g., the investment (amount) in a specific renewable energy project as the single parameter. A DS might then consider (among other things) the estimated cash flows, the risk involved, and the CO_2-saved as objectives. While the example might resemble a quite structured problem, a DS would need to help resolve potentially conflicting objectives. Depending on the types of objectives, different solution approaches (cf. III.4) might be applicable.

Multi-objective-multi-parameter

Analogously to the single objective type of decision problems, many decision problems that feature multi-objectives depend on more than a single parameter. In RA4, a

[8] In the minimal two asset case.

regulatory authority faces the challenge to set retail electricity rate structures (consisting of potentially arbitrarily many (rate) components serving as parameters) such that three important and partially conflicting ratemaking objectives are minimized.

III.4 Solution approaches

In order to address the decision problem types and the underlying objectives as discussed in section III.2 and section III.3, there are two generic approaches (Simon 1957). They are referred to as the "optimizing" and "satisficing" approaches, which will be presented below. Both approaches are related to the rational model of decision-making and its corresponding process (Simon 1977a). Many researchers position their DS contributions following that process. In the field of EI, for example, Klör et al. (2018) link their DS design for repurposing electric vehicle batteries to that process model: In Simon (1977a)'s process model, there are four steps, which follow in sequence. Nonetheless, the process may be iterative. First, there is an intelligence phase. Its purpose is to set the objective(s) (if applicable), gather all relevant data, and understand the decision parameter(s). The output of the intelligence phase is the decision problem. Second, there is the design phase, where the model connects the decision parameter(s) to the objective(s) as well as the constraints restricting the design space. The outcome of this process phase are the identified decision alternatives. Third, the choice phase comprises all activities related to choosing one course of action among the identified decision alternatives, i.e., making the decision, which also is the outcome of the process phase. Lastly, in the fourth and final step, the decision is executed and put into implementation. This phase includes a result-based decision evaluation. The decision process underlying the solution approaches is depicted in Figure 4. Both solution approaches are presented hereafter.

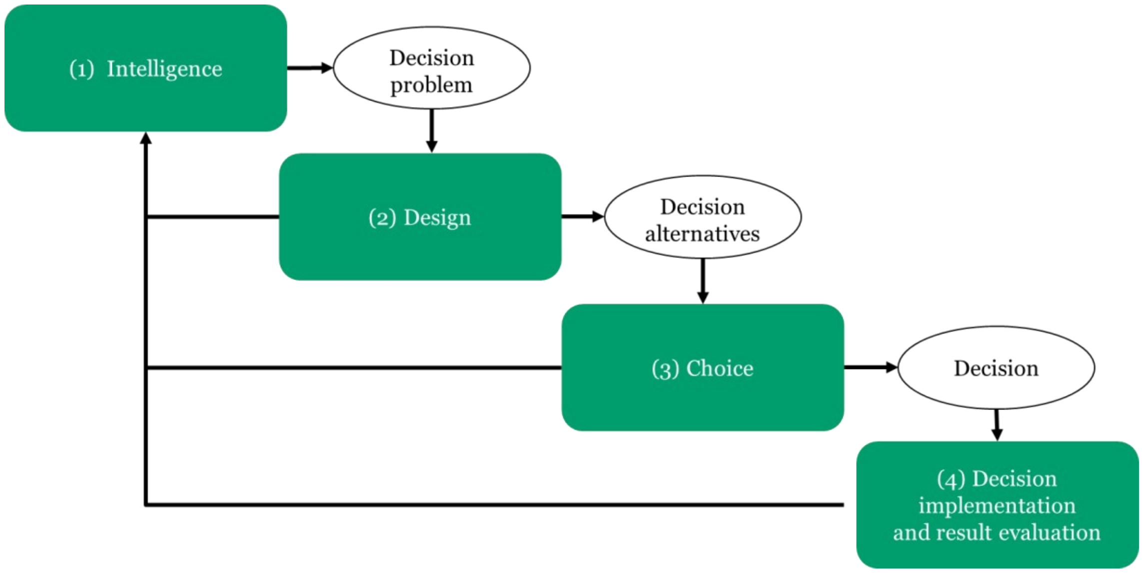

Figure 4 Simon's process model of rational decision-making adapted from Simon (1977a).

Optimizing approach

When following the optimizing approach to decision-making the decision process as described above is executed with two assumptions in mind. First, it assumes that a fully informed rational decision-maker (cf. III.5) carries out the decision-making. Second, the decision-maker aims at identifying the best feasible decision alternative regarding at least one objective. DS supporting this approach draw on theories from operations research and management science. According to Simon (1978), theories from these fields specify "good (or best) methods for finding good (or best) decisions in complex managerial situations. Operations research theory is a theory of computation, of procedural rationality."

Contrary to an optimizing approach with a single objective, there typically does not exist an unambiguous optimum with multi-objective problems. There would only exist exactly one in the very rare case of perfectly aligned objectives. In all other cases, DS need to trade off the objectives. According to Wang et al. (2009), especially problems in the energy domain and thus EI tend to have multiple objectives.

Satisficing approach

In contrast to the optimizing approach and according to Winter (2000), the satisficing approach represents a theory of choice that rather focuses "on the process by which alternatives are examined and assessed". Instead of finding the best alternative the satisficing approach is directed toward identifying one alternative that suffices, i.e., it is “good enough to do the job”. Decision-makers following this approach necessarily consider the effort required to identify the best alternative. This is because a decision-maker would otherwise opt for the optimizing approach. Note that the optimizing and satisficing approaches are the same when there is only a single feasible solution. As implications from the definition of the satisficing approach, we can state the following findings in accordance with Winter (2000) and Filip et al. (2017). First, human decision-makers are prone to the satisficing approach. This is considered to be due to humans’ limitations, mostly cognitive capabilities (Simon 1955, 1960). However, even supported by DS, a human might choose the satisficing for the following practical limitations: time constraints, no data, low data quality, costs for data gathering, and costs for data processing (Filip et al. 2017). Second, the identification of one solution meeting the requirements ends the search process. Third, when adding a certain level of aspiration as a constraint, optimality can be approximated. Many heuristic approaches consider this intermediate approach (Simon and Newell 1958).

III.5 Decision-maker types

One of the most important concepts in decision-making is the entity ruling the decision, i.e., choosing from the menu of alternatives. The decision-maker, however, does not necessarily execute the decision, i.e., performing the course of actions following up on the decision. In addition, a decision-maker not necessarily needs to be the user or the builder of the DS. Thus, while a decision-maker is one important entity, for a DS, there are several notable other roles involved in DS-based decision-making, which, however, are not equally applicable to all DS. That is why, in this thesis, I focus on the prominent decision-maker role and refer to Sprague (1980) for other conceivable roles.

Regarding the decision-maker, it is most important to distinguish between a human choosing a decision alternative and the DS choosing a decision alternative. Especially in the field of EI, this is a central distinction because many analytically complex decisions need to be made within timeframes evading human cognitive abilities. Among human decision-maker types, there is also an important distinction, namely between individuals and so-called decision units. I first present these types of decision-makers before turning to DS as decision-makers. Concerning DS as decision-makers, there is also an important distinction between programmed DS and AI-based DS, which I present in detail hereafter.

Human: Individual

Human decision-makers in contrast to non-human decision-makers (computerized DS) fall victim to several cognitive limitations (Simon 1955, 1957) as referred to as bounded rationality (Simon 1972). Humans' limits and constraints do not only depend on the decision-maker him-/herself but on the decision situation, the decision-maker is facing. For example, a defective set of solar panels will cause different levels of havoc depending on whether it is a house owner facing the problem or an astronaut on the international space station. For an extensive list of potential limitations of human decision-makers and how DS can help them overcome or at least soften those limitations, I refer to Holsapple and Whinston (1996).

Human: Decision unit

In addition to individuals (humans), many decisions are subject to the consent of a group of humans. In this thesis, I generally refer to this type of decision-maker as a decision unit. A decision unit is composed of two or more individuals with potentially varying levels of power, duration of the decision unit's existence, composition, and individuals' (potentially conflicting) goals, and an extended team supporting the individuals agreeing and making the decision (Holsapple and Whinston 1996). EI research frequently targets problems by policymakers who face challenges arising from the ones described above and which are related to decision units. DS that are particularly designed to improve the decision-making of decision units, therefore, represent a distinct class of IT artifacts.

System: Programmed

In lieu of humans, a DS can choose among possible decision alternatives. While this is generally possible, there are two important distinct classes that EI researchers will want to differentiate when they design their contributions. First, there is the programmed DS, which executes decisions according to the rules it was programmed to stick with. These rules can be arbitrarily complex, though. It is debated in literature, whether this type of DS can be considered a decision-maker since it merely executes the immediate will of its programmer(s) (Pomerol 1997). One very prominent example of such DS is the execution of smart contracts on Blockchain-based systems, which follow an "if-this-then-that"-paradigm (Fridgen et al. 2019).

System: Artificial-Intelligence-based

Second, AI-based systems make decisions that were not programmed intentionally by the system's creators but are a result of the input data the AI-based DS was trained on. When the system is confronted with data patterns atypical to the data it was trained on, it might choose a decision alternative leading to potentially undesired outcomes. Crashes by autonomous vehicles for example confusing a truck’s canvas cover for the sky are widely discussed (Banks et al. 2018). Irrespective of their potential threat, this class of DS makes autonomous decisions that have not been programmed but emerge from computational techniques applied to some set(s) of data.

III.6 Analytics types

Systems either supporting human decision-makers or conducting decisions in lieu of a human decision-maker perform acts of investigation and intelligence (which I refer to as analytics in line with Watson (2014)). It is relevant to highlight that this does not necessarily involve an artificial-intelligence-based approach. Analytics approaches that are based on (mathematical) optimization and simulation are equally applicable. Depending on the role of the DS, different types of analytics are required. In turn, the role of a DS in a decision-making process is related to what types of questions it has to address and the desired degree of decision-making automation, i.e., how much human involvement is necessary to make and implement the decision. For all types of analytics, input is data while output is the measurable effect of actions following the decision. In addition, the type of analytics and its level of (technical) sophistication do not imply effectiveness. Nonetheless and according to Watson (2014), this distinction of DS types is “because the differences have implications for the technologies and architectures used.” Figure 5 summarizes all analytics types and their degree of necessary involvement by the decision-maker (either human or system-based).

Descriptive analytics

DS supporting descriptive analytics address questions regarding “what happened?”. Descriptive analytics’ nature is retrospection and looks at historical data without inferring about the present or future. Many (energy) reporting dashboards and scoring boards using standardized reports follow this kind of analytics. According to Fischer et al. (2020), the TCP Link Smart Plug Energy Monitoring that provides power consumption data is one notable example from the building energy domain.

Diagnostic analytics

In contrast to descriptive analytics, however, DS assisting in diagnostic analytics strive to address questions regarding “why did something happen?”, i.e., it strives to discover previously unknown causal relationships based on historical data (Fischer et al. 2020). This is why it is also referred to as exploratory or discovery analytics (Watson 2014). Diagnostic analytics and its corresponding DS are linked to descriptive analytics in that they both study the past to learn for the future. Therefore, diagnostic analytics also requires a human decision-maker to synthesize and leverage the intelligence provided by the DS to carry out the decisions and put them into action. DS supporting this type of analytics oftentimes join disparate and large data sets having diverse levels of data quality, e.g., as is the case for RA 2 and RA3. For that reason, fewer statistical and more computational techniques are in place.

Predictive analytics

In contrast to descriptive and diagnostic analytics, predictive analytics uses relationships in historical data to make predictions about future events or unknown objects. Predictive analytics thus addresses questions relating to “what might happen?“ or “what might be?”. For example, wind turbine manufacturers may provide scheduled but aperiodic maintenance intervals instead of periodically planned ones for reasons of cost-effectiveness. This can become possible when predictive analytics allows the prediction of defects based on time series data from sensors. Computational techniques then learn from these relationships and might predict future defects. Human involvement usually tends to decrease with predictive analytics (Sapp et al. 2018). Similarly, in RA3 the authors apply an artificial neural network to predict the building energy demand for heating end-uses for yet unknown buildings in a given year. In that piece of research, the authors also demonstrate that a trained machine learning model originally designed for diagnostic analytics can be repurposed for predictive analytics and vice versa.

Prescriptive analytics

While predictive analytics might tell a decision-maker what might happen prescriptive analytics supports human decision-makers with information on “what should be done?”. As mentioned, a DS can potentially automatically (autonomously) implement the decision to execute the action upon the decision. For this type of analytics, human involvement is consequently the lowest. For prescriptive analytics, there are thus two subtypes. The first subtype provides decision support on what should be done. This requires the human decision-maker to initiate the action that implements the decision. In the automation subtype, the human decision-maker has passed on the rights to the system to execute the decision without requiring him/her to intervene. Figure 5 presents all analytics types, in-/output, and human involvement.

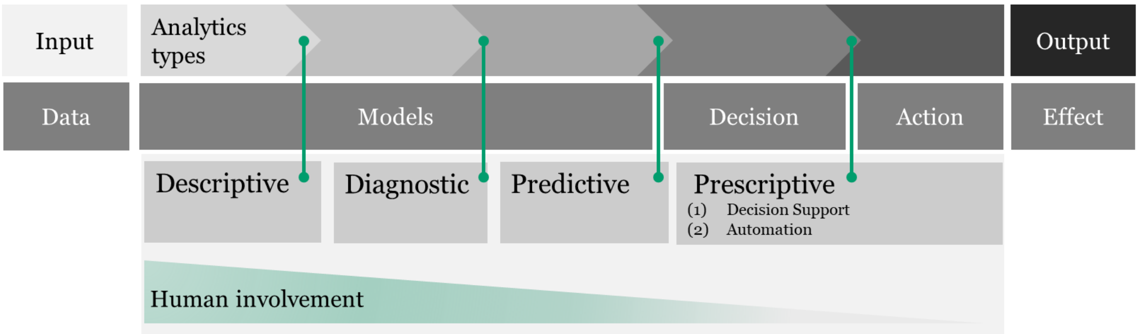

Figure 5 Degrees of human involvement depending on the type of analytics adapted from Sapp et al. (2018)

IV. Dimensions of Decision Systems in Energy Informatics

As mentioned in section I.2, this chapter sets out to summarize the constituting dimensions of DS designs in EI described. Based on those dimensions, this chapter portrays the individual contributions of this cumulative thesis. The RAs attached in the appendix serve as instances of DS in EI. I present them along the constituting dimensions of DS from chapter II and EI from chapter III.

Components of a DS, stakeholders, and goals are three invariants within this representation of DS in EI. However, there are nine dimensions (four relating to EI and five relating to DS) that characterize contributions in the field of DS in EI. The dimensions are numbered from (1) to (9) and presented in Figure 6. The RAs' content is presented in the appendix as abstracts with references to the published full papers. In this chapter, I limit my explanations to assessing the RAs regarding the nine dimensions as introduced in the chapters above. I elaborate on the RAs in ascending order, i.e., the same order as they are listed in the appendix.

Decision (support) systems in Energy Informatics						Source
Invariants – EI – Stakeholders	II.1	Governments	Suppliers	Consumers		Watson et al. (2010)
Invariants – EI – Goals	II.2	Eco-efficiency	Eco-effectiveness	Eco-equity		Dydlick & Hockerts (2002), Watson et al. (2010)
Invariants – DS – Components	III.1	Dialog	Data	Models		Sprague (1980)
Energy Informatics						
(1) Energy system technologies	II.4	Demand	Supply	Integrated	Multi-energy systems	(Watson et al. 2010) (Goebel et al. 2014) (Huang et al. 2017)
(2) Life-cycle stage	II.5	Planning / Investment	Operation	Repurpose	Disposal	Melville (2010) Klör (2016)
(3) Function IS (=DS)	II.6	Information	Incentives	Incentive-based direct control	Direct control	Braun & Strauss (2008)
(4) Energy accounting level	II.7	Energy (end-use) sectors	Energy carrier types	Objects		This thesis
Decisison Systems						
(5) Problem type	III.2	Structured	Ill-structured	Unstructured (wicked)		Simon (1973) Rittel & Webber (1973)
(6) Objectives	III.3	Single-objective single-parameter	Single-objective multiple parameter	Multi-objective single-parameter	Multi-objective multiple-parameter	Keeney et al. (2003)
(7) Solution approach	III.4	Optimizing		Satisficing		Simon(1957)
(8) Decision-maker type	III.5	Human: Individual	Human: Decision unit	System: Programmed	System: AI-based	Hackathorn & Keen(1981),
(9) Analytics type	III.6	Descriptive	Diagnostic	Predictive	Prescrptive	Watson (2018)

Figure 6 Overview of the dimensions of DS in EI as introduced in chapter II and chapter III.

IV.1 Classification of this thesis' contributions

Research article 1. This piece of research considers two data centers located in two separate balancing power markets. It studies the economic viability of providing balancing power from the market region with lower costs for balancing power to the market with comparatively higher costs. Therefore, the DS considers both energy system technologies for supply and demand (i.e., integrated) (1). The DS is in place during the lifecycle stage of "operation" (2). It bids on the balancing power market in one region and receives a premium in return for accepting balancing power calls, i.e., the requirement to increase or decrease supply or demand, respectively (incentive-based control (3)). The DS accounts for energy per kilowatt electricity demand and is thus energy-carrier-based (4). The problem is relatively well-structured (5) as it is a single-objective-multiple-parameter decision problem (6), and only considers tangible economic benefit (objective) and bids (parameters). The DS employs a simple heuristic without aspiration levels and therefore follows the satisficing approach (7). The DS' decision-maker is the programmed system itself (8) and thus necessarily constitutes an example for prescriptive analytics (9).

Research article 2. In RA2, the authors study a DS supporting make-and-buy decisions by electricity distribution network operators for mitigating distribution grid imbalances. The DNO supplies positive or negative balancing power (1) during the operation phase (2) and directly controls energy resources for its make-option (3). The imbalances are accounted for on an energy carrier level (4). The underlying problem ranges amid the spectrum of structuredness. This is because there is a clearly defined economic objective. However, if environmental metrics should be modeled only as constraints or even as objectives is debatable. In addition, little environmental data are available, e.g., the accurate emission factors of specific energy resources. Thus, the DS adds structure to an actually ill-structured problem at the expense of generality (5). In turn, the problem becomes a simpler, single-objective one (6). As the DS only helps identify good results rather than the best possible result, the DS follows the satisficing approach (7) in an automated fashion by a programmed system-based decision-maker (8). It thus delivers prescriptive analytics (9) as the basis for system-based decision-making.

Research article 3. In RA3, the authors design a data-driven DS for energy demand estimation (1) of single- and two-family buildings (4). The DS serves a human decision-maker as support (namely, the building owner) (8) for planning and investments (2) in building energy retrofits through information provision (3). The DS provides predictive decision support for after-retrofit demand but can also deliver diagnostic analytics to identify reasons for high/low demand (9). The problem is considered rather well-structured (5) since energy demand is easily measurable such that the prediction accuracy of a DS can be measured as well. Additionally, there is also plenty of data available to date. The problem is grounded on multiple input parameters and targets at a single objective, namely, the actual prediction accuracy (6). The DS provides information for any combination of the building parameters but does not strive to identify the optimal retrofit (combination) and therefore represents a typical exemplar of a DS in EI that follows the satisficing approach (7).

Research article 4. In RA4, the authors propose a DS for a regulatory authority, i.e., a non-homogenous decision unit (8), in the electricity end-use sector (4). The DS helps the regulator in its decision-making processes for the approval of rate structures by public utilities, i.e., at the time of planning and projecting investments (2). To do so, it considers both energy technologies on the supply and the demand side (1). Designing and thus approving rate structures is a well-known wicked (unstructured) problem (5) (Ketter et al. 2016b). In this article, the authors were able to increase the problem's structuredness by demonstrating a way to operationalize hitherto qualitative ratemaking principles into a quantitative multi-objective-multi-parameter decision problem (6). They do so while incorporating positive feedback loops that are said to be the root cause of the wickedness by a simulation-based optimization approach (7). Eventually, the DS provides information to the decision unit as a predictive analytics service (9). Despite the DS' capability of identifying a Pareto-optimal set of rate structures, it will remain to political views, which rate structure among the Pareto-optimal should be chosen.

IV.2 Discussion and summary of Decision Systems in Energy Informatics

It is relevant to summarize and discuss the individual findings from classifying this thesis' RAs. Therefore, the dimension-wise summary and discussion support generalizing findings from the thesis' investigation of the interface of DS and EI. Where it contributes to the discussion, I reference and discuss literature from the field.

When studying the four RAs regarding the nine dimensions, there are 36 individual instances of the characteristics. Table 1 presents all instances in a structured format by the dimensions and articles discussed in section IV.1. The table presents horizontally the RAs while the nine dimensions are presented vertically. It is observable that all instances can be matched with available characteristics in the dimensions, i.e., no instance demands to make an exception from the identified sets of characteristics within the dimensions. Looking at the nine dimensions individually, there are several inherent findings.

First relating to energy technologies (1), all four RAs take either demand, supply, or an integrated perspective. This is three of four characteristics. The multi-energy systems perspective has not been addressed so far. However, it is noteworthy that the case study in RA2 connects two energy systems through a DS-informed aggregation of multiple small combined-heat-and-power plants (i.e., a multi-energy system perspective). However, the design intention of that piece of research was clearly to support the distribution network to supply balancing power rather than taking a multi-energy system perspective. For example, the DS artifact of RA2 can also work with electric batteries (i.e., electricity only). Interestingly, even when searching online directories, only very few and only most recent articles dare to tackle the complexity of multi-energy systems, e.g., Golla (2020).

Second, with regard to the lifecycle stage (2), there is both in this thesis and in external literature a focus on the planning/investment and operational phases (Klör 2016). However, given the challenges facing the circular economy (Liu et al. 2018) contributions targeting the repurposing (incl. remanufacturing, recycling, etc.) and the disposal phases will be of high relevance to addressing climate change and environmental problems, in general.

Third, regarding the function of IS (3), we observe that even in this thesis the IS takes on a variety of roles and functions: spanning from the mere provision of information to direct control via intermediary steps such as incentive-based control. Only an IS, whose function is to only provide incentives, is not covered in the attached RAs. When turning to literature in the field of DS in EI, there appears to be an emphasis on the incentivizing role, e.g., via marketplaces (Golla et al. 2020). This may be due to IS' strong focus on its coordinating role and potential for the reduction of transaction costs (Malone et al. 1987).

Fourth, regarding the energy accounting level (4), both in this thesis and also in the extant body of EI literature, researchers already today examine all various energy account levels when studying problems and developing DS contributions in EI. On an object level, objects might relate to individual buildings as in RA3 or computing devices, and potentially also algorithms themselves (Fridgen et al. 2021). Likewise, research on energy carriers (Fridgen et al. 2016) or energy sector levels (Fridgen et al. 2020) are prevalent. Thus, qualitatively at least, no gaps can be identified.

Fifth, regarding decision problem types (5), there are few research endeavors in EI (not only in this thesis) daring to address unstructured and wicked problems that stem from the complexity that is imposed by the plenitude of stakeholders, goals, and drivers of change simultaneously. However, given the urgency and criticality of the climate and environmental challenges, it remains to research to demonstrate its impact. To that end, by RA4, this thesis provides a limited but effective solution-oriented DS specifically addressing a previously believed completely unstructured problem. Some researchers thus termed ratemaking an “art” rather than science (Caywood 1972; Graeser 1978).

Sixth, regarding the number of objectives and parameters (6), compared to the broader domain of energy research, where there is a vast body of impactful contributions (Cui et al. 2017; Fadaee and Radzi 2012; Perera et al. 2013) on multi-objectives problems, in DS in EI there are only a few such contributions to date.

Seventh and regarding the solution approach (7), no dominant approach can be identified. It remains an open question when the modeling error dominates the error from not trying to identify the theoretically optimal solution. A satisficing approach is typically the preferable choice when the modeling error dominates. In the case of building energy demand, RA3 provides guidance to make that distinction.

Eighth regarding the decision-maker type (8), while in this thesis all four types of decision-makers have a place, it is worth noting, that in the EI literature, human decision-makers types are dominant (cf. Klör 2016).

Finally and regarding the analytics type (9), this thesis contributes two RAs to predictive and two RAs to prescriptive analytics types, which are considered especially relevant for impactful research in IS (Chandra et al. 2015).

The concept has demonstrated its usefulness in supporting the classification of research in this growing field within IS. In addition, the concept allows identifying strengths and weaknesses in the current academic landscape regarding DS in EI. Moreover, it may be used to facilitate future research by helping other scientists to position their research within the field. Also, for practitioners, the concept might serve as a tool to navigate quickly through the academic landscape to foster knowledge transfers from academia into practice, e.g., by joint research and development efforts. Eventually, I rest confident that both researchers and practitioners find the concept helpful in that it makes necessary design decisions more transparent and allows faster comprehension of the core ideas behind DS in EI.

	RA1	**RA2**	**RA3**	**RA4**
1	Integrated	Supply	Demand	Integrated
2	Operation	Operation	Planning/ Investment	Planning/Investment
3	Incentive-based control	Direct control	Information	Information
4	Energy-carrier	Energy- carrier	Object	Energy (end-use) sector
5	Structured	Ill-structured	Structured	Unstructured
6	SO-MP	SO-MP	SO-MP	MO-MP

7	Satisficing	Satisficing	Satisficing	Optimizing
8	System: Programmed	System: AI-based	Human: individual	Human: Decision unit
9	Prescriptive	Prescriptive	Predictive (diagnostic)	Predictive

Table 1 Summary of the application of the concept DS in EI on the four attached individual contributions in the appendix. SO (Single-objective); MO (Multi-objective); MP (Multi-parameter).

Figure 7 Graphical overview of the classifications of the attached RAs.

V. Conclusion

In this cumulative doctoral thesis, I adopted an – in accordance with Watson et al. (2010) – “information-biased Weltanschauung” to address climate change in general and the energy sector in specific because of its detrimental impact on climate change through massive volumes of emitted greenhouse gases. I argued that not very surprisingly–- but given the urgency and criticality of the problem–- also somewhat unfortunate, energy is continuing to be an important input factor to the world’s economic productivity. Consequentially, humankind’s prosperity and welfare depend on energy. This makes solutions to the energy consumption problem (Hoffert et al.

2002) an immensely difficult challenge – perhaps the hardest in the 21st century.

Beginning with Watson et al.'s (2010) inspiring opinion piece in the Management Information Systems Quarterly journal, by today a three-digit number of research articles have either directly subscribed to the EI theme or indirectly relate to it, e.g., via publications in the journal Energy Informatics. Among those articles, there are many solution-oriented contributions, of which again many fall in the class of DS. However, the DS sub-discipline is over five decades old and much of the fundamentals have to be restored each time an EI researcher aims at contributing at the crossroads of DS and EI. Therefore, inspired by the challenges faced when authoring the attached RAs, I wrote this thesis. I am hopeful that future researchers may find the condensed presentation of the topics on DS and EI helpful for their research inquiries.

In order to unravel the unit of analysis, namely DS in the EI domain, I have described the relevant dimensions in the application domain and relevant dimensions originating from the vast body of knowledge on DS. I then classified the RAs attached to this thesis. The dimensions demonstrated their usefulness in classifying the research I am involved in. In addition, they highlight similarities and differences among the research inquiries. It also helps shape the communication of the artifacts to other researchers. Eventually, it facilitated the finding that the thesis' contributions cover multiple design aspects, e.g., regarding the decision problem type or the function of the DS.

However, studying the interface of DS and EI also revealed that various areas of research within EI remain untouched, so far. For example, most research – both within this thesis and also within EI – avoid designing DS for unstructured problems. Additionally, there is a void regarding end-of-lifecycle energy systems. Only very few articles put their focus on repurposing and – to the best of my knowledge – none look into the disposal phase.

While I have put much effort into accumulating knowledge, it is a good scientific practice to openly discuss the limitations regarding the scope and rigor of the analysis. First, the research considered in this thesis is limited to all articles subscribing to the EI theme or have been published in the journal Energy Informatics. However, there certainly is research within the many journals in the energy domain that might fall within the scope of EI without referring to it. Second, the dimensions of EI in DS, that I presented, serve as an initial step toward better understanding and distinguishing concepts and phenomena in the EI field. From a practitioner's point of view, this might be valuable. Nonetheless, this synthesis is not to be confused with a rigorous morphological or taxonomical classification, oftentimes part of high-profile IS research. Thirdly and lastly, while not in the scope of this thesis, research might find it helpful to study archetypes of DS in EI similarly to Power (2004), who presents archetypes of systems for decision support with significant user involvement.

As part of the introduction, I stated five targets as desired contributions by this thesis, which I briefly repeat for readability's sake. In addition, I shortly summarize why I rest confident to have adequately addressed them:

- **Solution-orientation.** Impact is probably not an unambiguous term. Nonetheless, whenever solution-orientation can serve as a surrogate, the reader finds all four RAs to support this surrogate. However, it is also obvious that only solutions that find broad adoption can be relevant in the end. At the time of this thesis' publication, that remains to be seen. Notable to that end potentially is, however, one RA in 'Applied Energy', which I co-authored in addition to the RAs attached to this thesis. In that RA, the DS suggests not to build a stationary electrical storage for the case study at the large-scale charging park near Augsburg, Germany. This proposal is about to be realized at the time I write this thesis. Also concerning RA2, there now is empirical evidence of DNO actively managing local networks (Koch and Maskos 2020). While it is unclear how DNO perform the necessary action, it yet suggests the efficacy of DS like the one I presented in RA2.
- **Environmental focus.** Solution-orientation as described before may be a supporting principle to impactful research. To that end, other research has already highlighted IS' meaningful contributions to productivity increases in the 20th century. However, these drastic improvements have been absent with regard to increases in environmental friendliness (Gholami et al. 2016; Seidel et al. 2017; Staudt et al. 2019). In this regard, all four RAs positively contribute to the energy consumption problem (Hoffert et al. 2002). However, as I acknowledge, feasible solutions need to be in line with the external forces presented (cf. II.3). This puts harsh limits on the absolute levels of improvement. In contrast, in RA4 the DS supports regulators in making decisions regarding these forces, where we observe such relevant positive

changes. It is for this reason, I remain positive that EI research has a place in environmental policy and regulation.

- **DS' potential in EI.** Much of design-oriented research in IS is directed toward the development of sociotechnical artifacts such as DS (Becker et al. 2007). In EI, contributions belonging to this thesis and beyond often target well-structured problems. However, the unstructured and wicked problems often happen to be the most urgent and critical ones as stated before. Contributions based on simulation-based optimization for regulators and policymakers, e.g., RA4 and virtual testbeds (Ketter et al. 2016b) point out what is feasible when research dares to reap the full potential of DS to address lesser structured problems.
- **Design knowledge.** The attached RAs all present DS which are based on (kernel) theories. All presented DS artifacts tend to rest at the concrete end of the abstract-concreteness scale. While this might be an implication of EI's requirement to consider institutional frameworks (Goebel et al. 2014), it nonetheless complicates the development of mid-range theories relevant to larger parts of DS in EI. To that end, this thesis invites other researchers to explore the field and discover invariants in the form of mid-range theories. This thesis in turn offers a high-level synthesis of DS in EI, which is based on the individual contributions attached. Researchers following the challenging path of developing mid-range theories might find it helpful or seek inspiration from this thesis' synthesis, though.
- **Tangible exemplars.** As mentioned, this thesis contains both an abstract framework as well as four instances that are mapped according to the nine dimensions of the framework. The RAs attached present concrete DS designs that other researchers can reproduce, extend, deepen, or tailor to specific needs. The framework has demonstrated significant variety among the articles regarding the nine dimensions as discussed. Therefore, I am hopeful that the tangibility expressed by the exemplars serves as a relevant contribution to the field.

Summarizing, this thesis addresses a relevant and well-defined stream of research within EI, namely DS. This thesis may not serve as a starting point after a decade of research in EI but indeed shape the concepts relevant to the design of DS in EI's next decade. The impact of the next decade’s contributions is more important the lesser the impact of this decade’s ones.

VI. Acknowledgments

During all research projects and resultant articles, I worked with colleagues at the University of Augsburg, the University of Bayreuth, the University of Applied Sciences Augsburg, the Project Group Business and Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT), the Research Center Finance and Information Management (FIM), and the Lawrence Berkeley National Laboratory (LBNL). The research also built on previous and related work conducted within these organizations. Moreover, this thesis builds on the knowledge, processes, and culture of the aforementioned institutes, their leaders, employees, and students. Thus, I additionally wish to acknowledge specific previous contributions influencing my research.

RA1 continued work by Fridgen et al. (2015b) who studied the economic viability of integrating cloud-scale distributed data centers for transnational balancing power transactions. The proposed artifact is one instance of an investment in green data centers as discussed by Hertel and Wiesent (2014). In addition, cloud-scale electricity procurement on spot markets has been studied by Keller et al. (2020) using a real-options approach in line with Klaus et al. (2014) and based on methodological foundations by Ullrich (2013).

RA2 strongly relates to the stream of microgrid research despite its focus on distribution networks. To that end, it is inspired by previous work in that field discussing trade-offs between economic, ecological, and social design choices of microgrids and energy cooperatives managing them (Fridgen et al. 2015a). From an economic perspective, recent discussions on microgrid rate design play a crucial input in the design of the model (Fridgen et al. 2018). Eventually, the model from RA2 touches the dimensions of the microgrid framework as discussed by Sachs et al. (2019).

RA3 utilizes a data-driven approach to building energy quantification and finds that estimates can be more accurate than assessments by professional energy auditors even when conducting on-site inspections. RA3 analyzes data that has been studied in related research by my former colleagues (Niemierko et al. 2019; Töppel and Tränkler 2019) as part of the research project c.HANGE. This piece of research has been carried out as part of the research project "Big-Data-Analyse und -Prognose von Energieverbrauch und Sanierungskosten bei Immobilien" which has received financial support from the Bavarian Ministry of Economic Affairs, Regional Development and Energy (Grant No. IUK-1606-

0002//1UK491/001). I remain indebted for this opportunity to do research and work in the field of Energy Informatics and buildings as it provided the basis for my today's position as founder and managing director of a digital startup at the intersection of big data analytics and buildings.

RA4 presents a method to identify Pareto optimal retail electricity rates. I am grateful for the international cooperation project with the Berkeley Lab and its generous hosts supporting the project with research guidance and lab resources. The project fits well into the ongoing debate on rate design to which Rieger et al. (2016) and Fridgen et al. (2018) have contributed. The paper employs a simulation-based optimization approach based on a multi-objective genetic algorithm which may inspire future research endeavors in the field and beyond.

To that end, this thesis has benefitted largely from former research across a whole breadth of fields but also sets new stimuli regarding the touched themes in EI and the applied methods from DS.

Lastly and most importantly, I want to express my fullest and unconditional gratitude to my family, friends, and my beloved girlfriend who have been so patient when I was working uncountable hours on my dissertation, comforting me in times of failure, and always believing that I can do it. I am happy that perseverance is a shared value. It was you making me accomplish this.

Copyright Statement

The above sections are partly comprised of content taken from the research articles included in this thesis. To improve the readability of the text, I have omitted the standard labeling of these citations.

September 2023 *Lars Peter Wederhake*

VII. Appendix

VII.1 Declaration of Co-authorship and Individual Contribution

This cumulative thesis comprises four research articles (RAs) representing the main body of this work. All included RAs were written in teams with multiple co-authors. This section sets out to outline my individual contributions to each RA.

RA1 was written with three co-authors, who all contributed in equal parts to this article. My role in the research team centered mainly on developing the artifact. The research concept originated as a spin-off from a previous project of mine. In that vein, the team of authors tested the relevance of the idea in an earlier research-in-progress article (Fridgen et al. 2015b). As a result, I brought in a solid body of literature and references, on which this article is based. Also, at the core of my responsibilities was to further develop the artifact by conducting simulation studies to obtain results and derive comprehensive implications for policymakers. In addition, I substantially contributed to drafting the manuscript and preparing it for submission. Likewise, I later revised the paper in the course of the review process of the journal. Thus, I was substantially involved in all parts of the research project.

RA2 was written by me and two co-authors. As the leading author, I had multiple responsibilities in this research project. I ideated the research topic and initiated the research project. As a basis, I performed the investigation of the research problem. This allowed me to embed RA2 in the existing body of knowledge and to position the article in the unchartered territory while addressing a relevant research gap. Furthermore, I mainly developed the research methodology underlying RA2. Additionally, I took the lead in writing and preparing the manuscript for submission. Moreover, as the leading author, I was the only author carrying out the revision of the manuscript based on the peer reviewer's valuable comments. As this is the first piece of research my co-authors were involved in, I was also responsible for the project administration and supervision in line with my role as lead investigator and author.

RA3 was developed together with four co-authors. This RA is the first part of a two-part companion paper. The paper was split into two parts during the investigation of the research problem which I lead. The second part of the research is listed in further publications (cf. VII.6.2). The research endeavor (i.e., both parts) was initiated as part of a Bavarian research project that I managed as a research assistant. To that end, I assumed the responsibility to investigate the research problem, the research gaps, and its underlying hypotheses. The second paper establishes the theoretical foundation for RA3, while RA3 itself presents an artifact design and empirically evaluates it in practice (derived from the theory developed in the second paper). As all attached research papers shall only present tangible exemplars of solution-oriented research, only RA3 is directly attached to the doctoral thesis. For the second part, I refer all interested readers to further publications section VII.6.2. With regard to the research endeavor, I took a main role throughout the time from inception to completion. The other four authors advanced the paper with smaller but substantial contributions as two of the authors joined the paper team in the later course of the research endeavor, while one author took a supervisory role, and another contributed only to the early stages of the research endeavor. Regarding RA3, to which I am the first author as well, my responsibilities involved – apart from the investigation of the research problem - the conceptualization, the development of the applied methodology as well as the formal analysis of the design artifact. Additionally, I was mainly involved in writing the original draft of the manuscript as well as reviewing and editing before and after submission to the journal. Lastly, I was in charge of administrating the research project.

RA4 was written with four co-authors. Two of them worked at a national research laboratory in California during the time of the project, while my leading co-author and I spent some time in that laboratory and later finished the project in Germany. One subordinate co-author funded and supervised the project from Germany. The research project was in the majority conducted by the two leading authors, of which I am one. I contributed by developing the research methodology and its implementation in software. This involved the integration of a multi-objective simulation-based optimization approach. Additionally, the paper benefitted by a large degree from previous literature and works across a wide range of distinctly interdisciplinary fields, which I gathered, compiled, and distilled. My responsibility in this project encompassed both the investigation as well as the validation of the design artifact. As the paper draws on much empirical data, I was heavily involved in data preparation and curation. Lastly, I shared the main responsibility of writing the original draft of the manuscript with my leading co-author. Summarizing, I took a central role in each part and phase of the project.

VII.2 Research article 1: Shifting Load through Space: the Economics of Spatial Demand Side Management Using Distributed Data Centers

Authors:

Gilbert Fridgen, Robert Keller, Markus Thimmel, Lars Wederhake

Published in: ***Energy Policy***

(VHB-JOURQUAL 3 Category: B; 2021 Impact Factor: 7.58)

Citation:

Fridgen, G., Keller, R., Thimmel, M., and Wederhake, L. 2017. "Shifting load through space–The economics of spatial demand side management using distributed data centers," *Energy Policy* (109), pp. 400-413 (doi: 10.1016/j.enpol.2017.07.018).

Abstract

Demand-side flexibility (DSF) in the electricity grid has become an active research area in recent years. While temporal flexibility (e.g. load shedding, load shifting) is already discussed intensively in literature, spatial load migration still is an under-researched type of DSF. Spatial load migration allows us to instantly migrate power-consuming activities among different locations. Data centers (DCs) are power-intensive and process information goods. Since information goods are easily transferable through communication networks, power-intensive processing of information goods is not necessarily tied to a specific location. Consequently, geographically distributed DCs inherit—in theory—a considerable potential to globally migrate load. We analyze the economics of spatially migrating load to provide balancing power using geographically distributed DCs. We assure that neither of the participating electricity grids will be burdened by this mechanism. By using historical data to evaluate our model, we find reasonable economic incentives to migrate positive as well as negative balancing power. In addition, we find that current scenarios favor the migration of negative balancing power. Our research thus reveals realistic opportunities to virtually transfer balancing power between different market areas worldwide.

VII.3 Research article 2: Make or Buy IT-based Decision Support for Grid Imbalance Settlement in Active Distribution Networks

Authors:

Lars Wederhake, Simon Schlephorst, Florian Zyprian

Published in: Energy Informatics

(VHB-JOURQUAL 3 Category: -; 2021 Impact Factor: 2.82)

Citation:

Wederhake, L., Schlephorst, S., and Zyprian, F. 2022. "Make or buy: IT-based decision support for grid imbalance settlement in smarter electricity networks," *Energy Informatics* (5:1) (doi: 10.1186/s42162-022-00217-4).

Abstract:

Decision (support) systems are a particularly important type of information system to energy informatics. A key challenge in energy informatics is that electricity supply must be in balance with demand at all times. More volatile renewable energy sources increase the relevance of electricity network balancing, i.e., imbalance settlement. Typically, electricity distribution network operators bought balancing power from external service providers (Buy option). Interestingly, however, more local energy resources help smarter electricity networks develop a Make option, as in our real-world evaluation. Choosing the better decision alternative within the relevant timeframes challenges human decision-making capabilities. Therefore, this research proposes a model-based decision system to improve the operators' decisions concerning Make or Buy under various levels of data quality represented by availability, granularity, and timeliness. The study reports savings up to 40% of costs for imbalance settlement supporting ambitious development efforts by the municipality we study in our real-world evaluation.

VII.4 Research article 3: Benchmarking building energy performance: Accuracy by involving occupants in collecting data - A case study in Germany

Authors:

Lars Wederhake, Simon Wenninger, Christian Wiethe, Gilbert Fridgen, Dominic Stirnweiß

Published in: Journal of Cleaner Production

(VHB-JOURQUAL 3 Category: B; 2021 Impact Factor: 11.07)

Citation:

Wederhake, L., Wenninger, S., Wiethe, C., Fridgen, G., and Stirnweiß, D. 2022. "Benchmarking building energy performance: Accuracy by involving occupants in collecting data - A case study in Germany," *Journal of Cleaner Production* (379), p. 134762 (doi: 10.1016/j.jclepro.2022.134762).

Abstract:

Energy performance certificates (EPC) aim to provide transparency about building energy performance (BEP) and benchmark buildings. Despite having qualified auditors examining buildings through on-site visits, BEP accuracy in EPCs is frequently criticized. Qualified auditors are often bound to engineering-based energy quantification methods. However, recent studies have revealed data-driven methods to be more accurate regarding benchmarking. Unlike engineering methods, data-driven methods can learn from data that non-experts might collect. This raises the question of whether data-driven methods allow for simplified data collection while still achieving the same accuracy as prescribed engineering-based methods. This study presents a method for selecting building variables, which even occupants can reliably collect and which at the same time contribute most to a data-driven method's predictive power. The method is tested and validated in a case study on a real-world data set containing 25,000 German single-family houses. Having all data collected by non-experts, results show that the data-driven method achieves about 35% higher accuracy than the currently used engineering method by qualified auditors. Our study proposes a stepwise method to design data-driven EPCs, outlines design recommendations, and derives policy implications.

VII.5 Research article 4: Designing Pareto optimal electricity retail rates when utility customers are prosumers

Authors:

Andrea Saumweber, Lars Wederhake, Gonçalo Cardoso, Gilbert Fridgen, Miguel Heleno

Published in: Energy Policy

(VHB-JOURQUAL 3 Category: B; 2021 Impact Factor: 7.58)

Citation:

Saumweber, A., Wederhake, L., Cardoso, G., Fridgen, G., and Heleno, M. 2021. "Designing Pareto optimal electricity retail rates when utility customers are prosumers," *Energy Policy* (156), p. 112339 (doi: 10.1016/j.enpol.2021.112339).

Abstract:

Electric retail rate design is relevant to utilities, their customers, and regulators: retail rates strongly impact a utility's revenue as well as its customers' electricity bills. Retail rates are also price signals and affect how customers use the electricity service. Changes in usage, in turn, affect a utility's cost for providing the service and the accomplishment of political goals, e.g., reducing greenhouse gas emissions. Regulators approving rate proposals for privately owned, vertically integrated utilities, ratemaking resort to generic and partially conflicting retail rate design principles for assessing a utility's proposed retail rates. However, prevalent ratemaking methods may not deliver retail rates that optimally accommodate these principles of retail rate design. They neglect customers' reactions on price signals. Due to the diffusion of distributed energy resources customers can systematically optimize their interactions with the electricity system. For this reason, we propose a novel ratemaking method, which formalizes the problem of designing retail rates as a multi-criteria decision problem. We derive ratemaking objectives from recognized retail rate design principles. Adopting a simulation-based optimization approach, we account for customer reactions. By a case study depicting a fictive Californian utility, we find that the resulting Pareto frontiers are useful in recognizing and balancing trade-offs among conflicting ratemaking objectives. Also, we see that prevailing rates for the general electricity service do not appear Pareto optimal.

VII.6 Further publications

VII.6.1 Research article 5: The influence of electric vehicle charging strategies on the sizing of electrical energy storage systems in charging hub microgrids

Authors:

Leon Haupt, Michael Schöpf, Lars Wederhake, Martin Weibelzahl

Published in: Applied Energy

(VHB-JOURQUAL 3 Category: -; 2021 Impact Factor: 11.45)

Citation:

Haupt, L., Schöpf, M., Wederhake, L., and Weibelzahl, M. 2020. "The influence of electric vehicle charging strategies on the sizing of electrical energy storage systems in charging hub microgrids," *Applied Energy* (273), p. 115231 (doi: 10.1016/j.apenergy.2020.115231).

Abstract:

Economic, ecologic, and social benefits support the rapid diffusion of grid-connected microgrids (MG). Economic feasibility still stands out as the primary goal of commercial MGs. A stationary electrical energy storage system (ESS) is often a central component of MGs, facilitating islanding and cost-effective management of main grid use. Therefore, previous research has focused on the sizing of stationary ESS. The advent of large-scale electric vehicle (EV) charging hub MGs (CHMGs) such as the one along the freeway A8 near Augsburg, Germany, profoundly changes the economically optimal capacity of stationary ESS. While it is well conceived that EVs can be aggregated and then compensated for stationary ESS, research still lacks quantifiable evidence and methodological guidance on how the charging strategy (immediate, controlled, bidirectional) influences the economically optimal capacity of the stationary ESS. To address this gap, this paper proposes a method that includes a mixed-integer linear programming model for scheduling decisions under various conceivable ESS capacities and provides scenario analyses on the EV charging strategies as well as on ESS cost. Thereby, the method thus identifies the economically optimal capacity of the ESS. The results show that in the considered CHMG near Augsburg, the stationary ESS sizing decision is relevant in all but extreme scenarios.

In particular, the economically optimal stationary ESS capacity soars if more than 65% of the EVs begin to charge immediately and the storage costs falls below 150 EUR/kWh. In contrast, smaller portions of controlled charging EVs can already drastically reduce stationary ESS. Remarkably, this paper also gives quantitative evidence that investments in bidirectional charging do not pay off in the CHMG near Augsburg.

VII.6.2 Research article 6: On the surplus accuracy of data-driven energy quantification methods in the residential sector

Authors:

Lars Wederhake, Simon Wenninger, Christian Wiethe, Gilbert Fridgen

Published in: Energy Informatics

(VHB-JOURQUAL 3 Category: -; 2021 Impact Factor: 2.82)

Citation:

Wederhake, L., Wenninger, S., Wiethe, C., and Fridgen, G. 2022. “On the surplus accuracy of data-driven energy quantification methods in the residential sector,” *Energy Informatics* (5:1) (doi: 10.1186/s42162-022-00194-8).

Abstract:

Increasing trust in energy performance certificates (EPCs) and drawing meaningful conclusions requires a robust and accurate determination of building energy performance (BEP). However, existing and by law prescribed engineering methods, relying on physical principles, are under debate for being error-prone in practice and ultimately inaccurate. Research has heralded data-driven methods, mostly machine learning algorithms, to be promising alternatives: various studies compare engineering and data-driven methods with a clear advantage for data-driven methods in terms of prediction accuracy for BEP. While previous studies only investigated the prediction accuracy for BEP, it yet remains unclear which reasons and cause–effect relationships lead to the surplus prediction accuracy of data-driven methods. In this study, we develop and discuss a theory on how data collection, the type of auditor, the energy quantification method, and its accuracy relate to one another. First, we introduce cause–effect relationships for quantifying BEP method-agnostically and investigate the influence of several design parameters, such as the expertise of the auditor issuing the EPC, to develop our theory. Second, we evaluate and discuss our theory with literature. We find that data-driven methods positively influence cause–effect relationships, compensating for deficits due to auditors’ lack of expertise, leading to high prediction accuracy. We provide recommendations for future research and practice to enable the informed use of data-driven methods.

VII.6.3 Research article 7: Reducing the Expectation-Performance Gap in EV Fast Charging by Managing Service Performance

Authors:

Stephanie Halbrügge, Lars Wederhake, Linda Wolf

Published in: Lecture Notes in Business Information Processing

(VHB-JOURQUAL 3 Category: C; 2021 Impact Factor: 0.85)

Citation:

Halbrügge, S., Wederhake, L., and Wolf, L. 2020. "Reducing the Expectation-Performance Gap in EV Fast Charging by Managing Service Performance," in *Exploring Service Science*, H. Nóvoa, M. Drăgoicea and N. Kühl (eds.), Cham: Springer International Publishing, pp. 47-61 (doi: 10.1007/978-3-030-38724-2_4).

Abstract:

Electric mobility is considered pivotal to decarbonising transport. The operation of fast charging services has become a mobility business model. Its value proposition rests on the promise that fast chargers re-empower drivers to fulfil their mobility needs within acceptable servicing times. This is in particular important when levels for tolerance are low like on long-distance journeys. That value proposition might set inflated customer expectations. Due to economic considerations and operational restrictions, charging park operators might not live up to these expectations. This leads to an expectation-performance gap, which has received little scientific attention, to date. This paper presents an information system (IS) design, which aims at reducing that gap by managing performance. Our findings indicate significant benefits by the IS and highlights further opportunities for the IS discipline. Also, this article invites researchers from service science to discover opportunities for better expectation management and further reduction of the identified gap.

VII.6.4 Research article 8: Decision Flexibility vs. Information Accuracy in Energy-intensive Businesses

Authors:

Gilbert Fridgen, Andrea Saumweber, Johannes Seyfried, Lars Wederhake

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Citation: Fridgen, G., Saumweber, A., Seyfried, J., and Wederhake, L. 2018. "Decision Flexibility vs. Information Accuracy in Energy-intensive Businesses," in *26th European Conference on Information Systems (ECIS)*.

Abstract:

Demand-side management and demand response are integral building blocks for environmental sustainability. Exchange-based power pricing serves as an economic mechanism to set incentives to shift demand to periods where prices are low. Low power prices also serve as an indicator for green(er) power, since high feed-ins from variable renewable sources push the electricity price downward. For businesses, minimizing electricity costs thus not only contributes to economic but also environmental sustainability. Hence, especially energy-intensive businesses can become greener and more competitive by integrating volatile electricity prices into their production planning activities. In this paper, we demonstrate that the length of the planning horizons is key to achieve more sustainable outcomes due to the trade-off between decision flexibility and information accuracy. Decision flexibility – i.e. the capability to shift processes – increases with longer planning horizons. Information accuracy – i.e. price accuracy – increases with shorter planning horizons. Information Systems (IS) can help to balance this trade-off. We follow a data-driven approach and derive both actual and predicted electricity spot prices from historic electricity intraday market data in Germany. We find that decision flexibility and information accuracy affect the planning horizon as conceived. First results indicate that more sustainable outcomes are achieved with longer planning horizons.

VII.6.5 Research article 9: Privacy Preserving Approach to Collaborative Systemic Risk Identification: the Use-case of Supply Chain Network

Authors:

Tirazheh Zare Garizy, Gilbert Fridgen, Lars Wederhake

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Citation

Zare Garizy, T., Fridgen, G., and Wederhake, L. 2018. “A Privacy Preserving Approach to Collaborative Systemic Risk Identification : the Use-case of Supply Chain Network,” *Security and Communication Networks* (doi: 10.1155/2018/3858592).

Abstract:

Globalization and outsourcing are two main factors which are leading to higher complexity of supply chain networks. Due to the strategic importance of having a sustainable network, it is necessary to have an enhanced supply chain network risk management. In a supply chain network many firms depend directly or indirectly on a specific supplier. In this regard, unknown risks of network's structure can endanger the whole supply chain network's robustness. In spite of the importance of risk identification of supply chain network, firms are not willing to exchange the structural information of their network. Firms are concerned about risking their strategic positioning or established connections in the network. The paper proposes to combine secure multiparty computation cryptography methods with risk identification algorithms from social network analysis to address this challenge. The combination enables structural risk identification of supply chain networks without endangering firms' competitive advantage.

VII.6.6 Research article 10: Hierarchische Eignungsprüfung von externen (Open) Data Sets für unternehmensinterne Analytics- und Machine-Learning-Projekte

Authors:

Matthias Kaiser, Dominic Stirnweiß, Lars Wederhake

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Citation:

Kaiser, M., Stirnweiß, D., and Wederhake, L. 2022. "Hierarchische Eignungsprüfung von externen (Open) Data Sets für unternehmensinterne Analytics- und Machine-Learning-Projekte," *HMD Praxis der Wirtschaftsinformatik* (doi: 10.1365/s40702-022-00842-3).

Abstract:

Unternehmen erkennen zunehmend die Bedeutung evidenzbasierter Entscheidungen. Insbesondere die zunehmende Nutzung unternehmensexterner und offener Datensätze (Open Data) fördert die Möglichkeiten evidenzbasierter Entscheidungen. Dabei basieren evidenzbasierte Entscheidungen mit diesen Datensätzen immer häufiger auf Analysen, welche mittels maschineller Lernverfahren bzw. Machine Learning (ML) vorbereitet oder durchgeführt werden. Weil der Inhalt und die Qualität und damit der Nutzen eines Datensatzes für solche Analyseverfahren im Vorfeld ungewiss ist, stellt die Auswahl und die Beschaffung von geeigneten Daten unabhängig vom ML-Verfahren eine Kernherausforderung dar. Dieser Beitrag stellt deshalb zum Zwecke der Effizienz ein hierarchisches Vorgehen vor. Mit diesem können schemabasierte Datensätze strukturiert und effektiv dahingehend überprüft werden, ob deren Qualität und inhaltliche Fit für einen bestimmten Anwendungsfall (z. B. eine wiederkehrende Entscheidungssituation) ausreichend ist. Im Beitrag beschreiben wir einen Anwendungsfall aus dem Bereich der datengestützten Energieverbrauchsprognose für Wohngebäude, bei dem der Aufwand für die Datensatzauswahl reduziert werden konnte.

VII.6.7 Research article 11: Opportunities and Challenges of DLT (Blockchain) in Mobility and Logistics

Authors:

Gilbert Fridgen, Nikolas Guggenberger, Thomas Hoeren, Wolfgang Prinz, Nils Urbach, Johannes Baur, Henning Brockmeyer, Wolfgang Gräther, Elisaweta Rabovskaja, Vincent Schlatt , André Schweizer, Johannes Sedlmeir, Lars Wederhake

Citation:

Fridgen, G., Guggenberger, N., Hoeren, T., Prinz, W., Urbach, N., Baur, J., Brockmeyer, H., Gräther, W., Rabovskaja, E., Schlatt, V., Schweizer, A., Sedlmeir, J., and Wederhake, L. 2019. *Opportunities and Challenges of DLT (Blockchain) in Mobility and Logistics*, available at https://eref.uni-bayreuth.de/55481/.

Abstract:

This report presents the economic potential, legal framework, and technical foundations required to understand distributed ledger (DL) / blockchain technology and illustrates the opportunities and challenges they present, especially in the mobility and logistics sectors. It was compiled by the blockchain laboratory at Fraunhofer FIT on behalf of the German Federal Ministry of Transport and Digital Infrastructure (BMVI). Its intended audience comprises young companies seeking, for example, a legal assessment of data protection issues related to DL and blockchain technologies, decisionmakers in the private sector wishing concrete examples to help them understand how this technology can impact existing and emerging markets and which measures might be sensible from a business perspective, public policymakers and politicians wishing to familiarize themselves with this topic in order to take a position, particularly in the mobility and logistics sectors, and members of the general public interested in the technology and its potential. The report does not specifically address those with a purely academic or scientific interest in these topics, although parts of it definitely reflect the current state of academic discussion.

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