Autonomous Information Systems for Energy Prosumers: User Behavior & Economic Viability

Masterarbeit

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List of Abbreviations

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Introduction

The energy transition is a fundamental challenge of the 21st century and requires innovative technologies for humanity. This involves the energy sector moving towards more renewable energy sources and decentralization. There is also a coupling of different areas such as heating or mobility (Antonoupoulus et al. 2020). As a result, electricity demand will more than double in the future, projected to reach approximately 52,000–71,000 TWh by 2050, which is disproportionate to other energy sources (McKingsey & Company 2023). In order to ensure the demand-based generation and provision of energy, intelligent control and networking are required. In a study by the acatech, DFKI and Fraunhofer institutes, experts state that the increasing complexity will “not be manageable without the use of autonomous systems” (Duitrescu et al. 2018: 25). There is a massive increase in data that needs to be evaluated in real-time (Ponnusamy et al. 2021). In this work, autonomous information systems (AIS) are explored, which can independently analyze information and make decisions regarding energy management. People remain a central factor that technology is geared towards. In the course of the energy transition, the role of the end user is changing and they can play an active role as prosumers of energy (Parag & Sovacool 2016; Parra-Dominguez 2023). AIS are aimed at prosumers and are intended to improve their energy management. They address the intersection of technological, economic and human dimensions. Literature sources that combine both complex technology with user aspects are rare which is the addressed research gap. It is essential that technologies are developed withuser centricity (Rane et al. 2024). AIS is closely linked to artificial intelligence (AI) which enables learning systems. However, AI systems are often black boxes which affect users' trust (Venkatesh et al. 2022). The main focus is on the residential prosumer, which means that the technology affects the user personally and the accpetance can be characterised by even more human factors (Zheng et al. 2024). In general, the concept of AIS is also applicable to commercial prosumers, making some areas of the work transferable.

Even if the focus is on optimising the energy management of the individual prosumer, the interrelation with the overall system is very clear, whereby the information flow of the AIS goes beyond the household. Demand response enables prosumers to contribute to adjusting their demand in order to stabilize the grid and achieve financial benefits in return (Parra-Dominguez et al. 2023). Aggregators can bundle several prosumers to enable them to participate in the market, whereby the goal of AIS must be an economically viable product (Kerscher & Arboleya). The use of AI is not an end in itself, which also relates to AIS. It should always always solve a specific problem and generate added value (BDEW 2020).

Due to the interrelationships, the scope of the work goes beyond the individual household, with the benefits for the prosumer taking centre stage. The research process is based on two research questions which address different dimensions.

RQ1: What are the chances and challenges of autonomous information systems for energy prosumers?

RQ2: Which factors and aspects influence the user acceptance of energy prosumers?

The collected knowledge will be used to contribute to practice, highlighting design principles for AIS. A detailed description of the approach follows the introduction to the theoretical background in Chapter 2, where AIS is further defined and fundamental concepts are introduced. The work follows the iterative Design Science Research (DSR) approach, using a mixed-method approach of quantitative and qualitative data to obtain different perspectives. Chapter 3 describes the approach and individual methods in detail to understand the logical flow of the work. Chapter 4 presents the literature review according to Webster & Watson (2002), which forms the foundation of the work and encompasses all dimensions. In Chapter 5, the results of the qualitative, semi-structured expert interviews are brought together, which provide valuable knowledge and new perspectives from practice, stimulating further exploration. Chapter 6 contains the results of our own quantitative user survey, which is based on the literature surrounding UTAUT2 and addresses AIS more specifically than previous surveys. In chapter 7 werden dei ergebnisse consolidiert und synergien gebildet. The research questions are answered specifically and the design principles are presented. This is followed by a context for the work and limitations that encourage further research. Finally, Chapter 8 concludes the thesis and concludes with a brief outlook.

2 Theortical background

The theoretical section introduces the key concepts and technologies that are crucial for understanding autonomous information systems in the context of energy prosumers. Due to the number of concepts, the descriptions are on a high level to not go beyond the scope. Firstly, autonomous information systems are defined as the basis for this work and enabling technologies are introduced. This is followed by a discussion of the central concepts in the smart energy sector, which are closely interlinked.
The final section deals with the psychological dimension of the user. Well-known theories are discussed. The background is a basis for the following literature review.

2.1 Autonomous Information Systems and enabling Technologies

Autonomous systems and artificial intelligence in particular are currently topics of utmost relevance and the terms are used very frequently. It is therefore important to create clear definitions and demarcations. There are hardly any definitions for AIS, which is why the definition is oriented n based on autonomous systems.
According to the Frauenhofer Institute (Adler 2019): „A system is described as autonomous if it can achieve a predetermined goal independently and adapted to the situation without human control or detailed programming."
The same author summarises for the BIDT several definitions of **autonomous systems** and emphasises the following concise characteristics: *Independent actions without human control,*

8 Conclusion and Outlook

As part of the challenge of the energy transition and the complexity of integrating prosumers, AIS was analysed as an enabling technology for prosumers. Several dimensions were combined and synergies were created between technology, the user and economic aspects. This addresses the research gap mentioned at the beginning of the paper, whereby the inclusion of the user is essential in research on new technologies. Two research questions were posed in the introduction, with RQ1 covering the economic and technical side with the opportunities and challenges of AIS. On the other hand, RQ2 deals with the user and analyses decisive factors for acceptance. The two RQs are brought together in the discussion of design principles. The iterative DSR approach of Peffers et al. (2007) was orientated, whereby qualitative and quantitative methods were combined in order to build up a broad knowledge base. A literature review according to Webster & Watson (2002) was carried out as a basis. The python-based text-mining tool Orange was used to identify 6 key topics that helped to structure the review. The knowledge of the literature was used to conduct qualitative expert interviews and quantitative surveys. The expert interviews provided new insights that could be used for further exploration in the literature.

Overall, it became apparent that systems are not yet at an autonomous level. Predicting user behaviour is a particular hurdle. According to the definition of the work, AIS are self-learning and thus associated with AI as an enabling technology. In the context of the many uncertainties regarding generation from RES, consumptions and user preferences, AIS offers the chance of increased adaptivity. In line with this, forecasting was mentioned as a key application in the literature and expert interviews. In terms of adaptability, AIS offers the chance to further optimize themselves and to heal possible malfunctions. In line with this, anomalies in energy generation and consumption as well as possible attacks can also be detected. A larger topic is human-machine interaction, whereby the system can learn from possible user behaviour, which allows for increased individualisation. Conversely, the user can be informed by the interface, for example in the form of a graphical representation. The line is drawn to the user dimension in order to build trust. The concept of XAI is discussed in the context of the black box problem of AIS, whereby a certain degree of explainability is necessary for users. The experts point out new aspects, especially with regard to the challenges. The focus is not on technical barriers, but primarily on regulatory and market structural barriers. More incentives for consumers are needed to enable flexible energy management. Flexibility is closely linked to the economic viability of AIS as there is a high value potential for the overall system and cost savings for the individual. Another important challenge is the existing infrastructure where the smart meter rollout in particular is highlighted. Companies are also faced with the challenge of managing high volumes of data and need both IT infrastructure and professional expertise. Cost aspects of AIS are a further challenge, which calls for efficient solutions. The opportunities and challenges of AIS are clearly presented in table 17.

With regard to user acceptance, the UTAUT2 model by Venkatesh et al. (2012) was used as a basis for categorising factors.
According to the experts, it is questionable whether monetary incentives are currently

sufficient for the adoption of an AIS. The survey indicates that, above all, loss of control is a risk for users and that they want to be involved in energy management to a certain extent. The factors and aspects for answering RQ2 are shown in figure 51.
Finally, 21 design principles for implementers and concise external influencing factors were developed, whereby overlapping dimensions are made clear. Implementers can use the principles as a guide when developing and analysing AIS or related systems. The work can pave the way for more interdisciplinary research as described above.

Outlook

Overall, AIS should help to empower the prosumer and bring benefits to society as a whole. Intelligent systems are absolutely essential in order to react to fluctuating conditions in real time. The degree of autonomy must be further researched and should be increased step by step. The dynamic development of the energy sector and intelligent technologies relating to AIS must be pursued further. If the climate targets are to be pursued further, the electrification of various sectors is necessary. The importance of the interplay between generation and demand will increase in the future. The experts address the high costs of grid charges, which can also be passed on to users. In addition, price fluctuations could continue to rise, making AIS more profitable for prosumers. The EEG remuneration for feed-ins, which has been fixed for years, has already been affected by the Solar Peak Act. A more grid-friendly behaviour with incentives for prosumers would facilitate the need for AIS. In the context of the storage problem for RES, V2G & V2H have great cost saving potential, as the calculations by Rabot Energy (2025) and others show.
These technologies could encourage more people to purchase components such as PV and EVs. The increased smart meter rollout forms the basis for a networked energy system. A breakthrough in flexible tariffs could encourage more and more companies to develop new technologies and business models. In the context of the rise of AI, the interaction between humans and systems is an important field of research. It is essential that people become accustomed to cooperating with systems. As systems are not yet able to access the human brain directly, interaction is necessary. Intelligent systems lead to increased transparency and co-determination for prosumers compared to traditional electricity billing. As described by Campos et al. (2020), the identity of the self-determined prosumer could become a kind of movement. A certain threshold of adoption of AIS or intelligent systems must be reached for the development to gain momentum and for diffusion to reach the majority. The vision of P2P trading is raised in the literature and also by expert F, although this raises questions of financing and system integration. In general, coordination between the many different players in the energy sector is essential for progress, whereby the perspective of the end user must also be taken into account. It is important that all companies in a dynamic environment are open to change and do not restrictively cling to the status quo.
A possible optimistic vision of the future is a fully interconnected smart grid with various coordinated autonomous agents acting in the interest of individual prosumers.