Contributions to Decision Support Systems, Energy Economics, and Shared Micromobility Research

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Abstract

This thesis includes research articles on Decision Support Systems, Energy Informatics, and Economics, Shared Micromobility, and Digital Study Assistance. For many years, established Information Systems (IS) scholars have called for solution-oriented research to address the most pressing problems of climate change. In this context, this thesis summarizes three consecutive research articles that present the multi-year development of a Decision Support System (DSS) for the energy transformation of the building sector. The DSS Nano Energy System Simulator (*NESSI*) was developed using Design Science Research guidelines and was further field tested and evaluated with stakeholders. In the discipline of Energy Informatics, a research article is presented that provides a morphological box for the classification of real microgrids. Next, a research article is presented that used regression analysis to investigate the influences of factors on residential photovoltaic system prices and revealed spatial price heterogeneity in Germany.

Three research articles are outlined in the Shared Micromobility field. The first article uses a multi-year dataset of location data to examine the spatial and temporal use of e-scooters in Berlin. The second article builds on this and quantifies the influences of various factors such as weather, Covid-19 lockdowns, and other socio-economic parameters on the use of three micromobility concepts. The third article uses a web content mining process to collect a large dataset of police reports on e-scooter accidents. It analyzes risk factors as well as accident implications for riders. A research article on the requirements analysis and development of a digital study assistant concludes this thesis. Here, quantitative surveys and qualitative expert interviews are used to collect requirements from higher education institution stakeholders for a digital study assistant. In addition, developing a study assistance prototype is demonstrated and tested in the field.

Keywords: Decision Support Systems, Design Science Research, Energy Economics, Energy Informatics, Shared Micromobility, Spatiotemporal Analyses, Accident Analysis, Digital Study Assistance

Research Summary

This dissertation includes nine research articles, eight of which have been accepted or published, and one is under peer review. The nine research articles can be assigned to three diverse thematic clusters. The first cluster comprises the research disciplines of environmental decision support systems (DSS) in Information Systems (IS) Research, Energy Informatics, and Economics. The second cluster includes three research articles that investigate the temporal and spatial usage of micromobility and analyze the safety of e-scooter traffic. The third thematic cluster includes only one research article on digital study assistance. Table 1 provides an overview of all research articles, their association with a research domain, and the corresponding section.

Table 1: Research domains, sections, and research article titles.

Domains	**Section**	**Research Article Titles**
Decision Support Systems, Energy Informatics, and Energy Economics	2.1	Decision Support for Optimal Investments in Building Energy Systems
	2.2	Transformation to Sustainable Building Energy Systems: A Decision Support System
	2.3	Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Energy System Simulator NESSI
	2.4	Classification of Real-World Microgrids Based on a Morphological Analysis
	2.5	Disentangle the Price Dispersion of Residential Solar Photovoltaic Systems: Evidence from Germany
Shared Micromobility Usage and Safety	3.1	A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage
	3.2	Factors Influencing the Usage of Shared Micromobility: Implications from Berlin
	3.3	Web Content Mining Analysis of E-Scooter Crash Causes and Implications in Germany
Digital Study Assistance	4	User-centric Design, Development, and Evaluation of an Individual Digital Study Assistant for Higher Education Institutions

The following briefly describes the motivation and relevance of environmental DSS in IS research, Energy Informatics, and Economics. The 17 Sustainability Development Goals (SDGs) of the United Nations (UN) and the Paris Agreement of 2015 outline directives to mitigate the effects of global climate change. One of the key objectives is to drastically reduce CO_2 emissions across all sectors, such as energy supply, transport, and building and construction. The energy supply of buildings accounts for 30% of global energy consumption. In addition, building operations account for 27% of total energy sector emissions [1]. Thus, the transformation of the building sector holds immense potential for reducing global CO_2 emissions. Policymakers can accelerate this transformation through targeted measures, such as feed-in tariffs for renewable energy technology or subsidy programs for heat pumps. However, building decision-makers are responsible for making investment decisions. The development of DSS has a long tradition in the IS community [2]. With the emergence of Green IS and Energy Informatics, IS-induced DSS that address climate change issues are becoming more prominent [3]. Established IS researchers have been calling for years to leverage the transformative power of the IS discipline and provide solution-oriented artifacts for complex decision-making to tackle climate change [4, 5]. Research articles 2.1 to 2.3 present the development of the DSS *NESSI* (Nano Energy System Simulator) within a Design Science Research (DSR) project of more than four years. Its final version is designed to support decision-makers like residential and commercial building owners, housing associations, and energy consultants in transforming buildings to an emission-free energy supply.

2.1 Decision Support for Optimal Investments in Building Energy Systems

The first research article emerging from the *NESSI* DSR project initially addressed residential and commercial prosumers. Building owners who feed in electricity through renewable energy technologies are referred to as prosumers in academic literature [6]. The Renewable Energy Sources Act (EEG) has supported the feed-in of electricity from renewable sources in Germany since 2000. The steadily falling feed-in remuneration and dynamic price development of energy technologies have complicated the decision-making basis for prosumers. Two key issues have been identified for prosumers: (i) rooftop photovoltaic (PV) systems installed before 2000 will fall out of the remuneration scheme, and the question arises about the further operation and possibly the coupling with other components. (ii) a large share of system owners must increase the self-consumption of their PV systems, and the question arises as to how this goal can be achieved efficiently from an

economic point of view.
In the context of a DSR approach according to [7, 8], a MATLAB-based artifact for prosumer decision support is proposed. It addresses the question of how incremental investments optimally enhance building energy systems' efficiency? The artifact includes an energy system model that can simulate the operational management of various energy technology components at hourly time resolution over a year. The technical parameters used to model PV systems, battery power storage, hot water storage, heat pumps, and electric cars are outlined. Performance monitoring reports various key performance indicators (KPIs) such as degree of self-consumption, degree of autarky, and energy cost reduction.
A computational study demonstrates the applicability of the decision support artifact. As shown in Figure 1, the impact of incremental investments in PV systems, battery storage, and hot water storage on energy cost reduction can be quantified. Furthermore, the change in KPIs is shown to provide a more robust basis for decision-making.

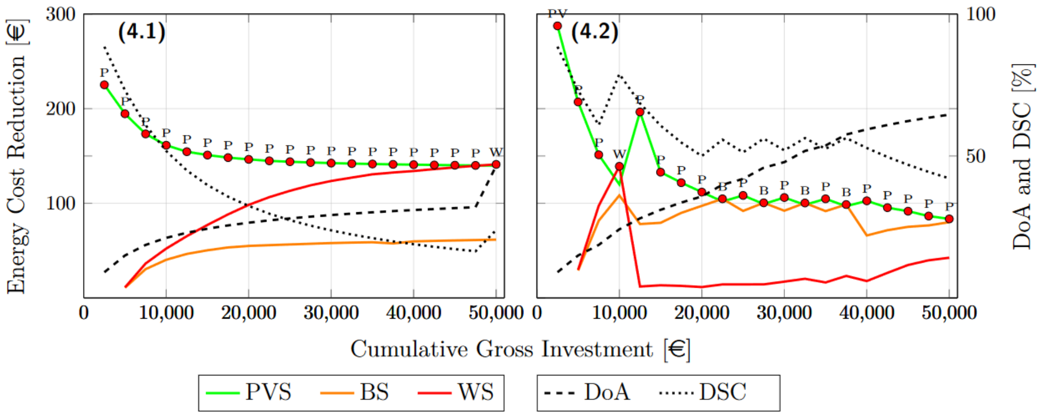

Figure 1: Overview of energy cost reduction for a four-person household.

The artifact architecture, underlying energy system model, and performance monitoring provide the foundation for further development into a comprehensive DSS. Research articles 2.2 and 2.3 build on the groundwork and core ideas of this article.

2.2 Transformation to Sustainable Building Energy Systems: A Decision Support System

Stemming from the prosumer focus, research article 2.1 generalized the problem formulation and opened it up to more stakeholders. Instead of the local reference to Germany, the global problem of the sustainable transformation of the building sector was defined as the DSR entry point. Residential and commercial building owners, housing associations, and energy consultants must be supported in transforming buildings toward an emission-free energy supply. Addressing this problem, the user-centered and solution-oriented DSS *NESSI* is proposed according to the DSR publication scheme of [9]. The development process was embedded in the three-cycle view of [10].

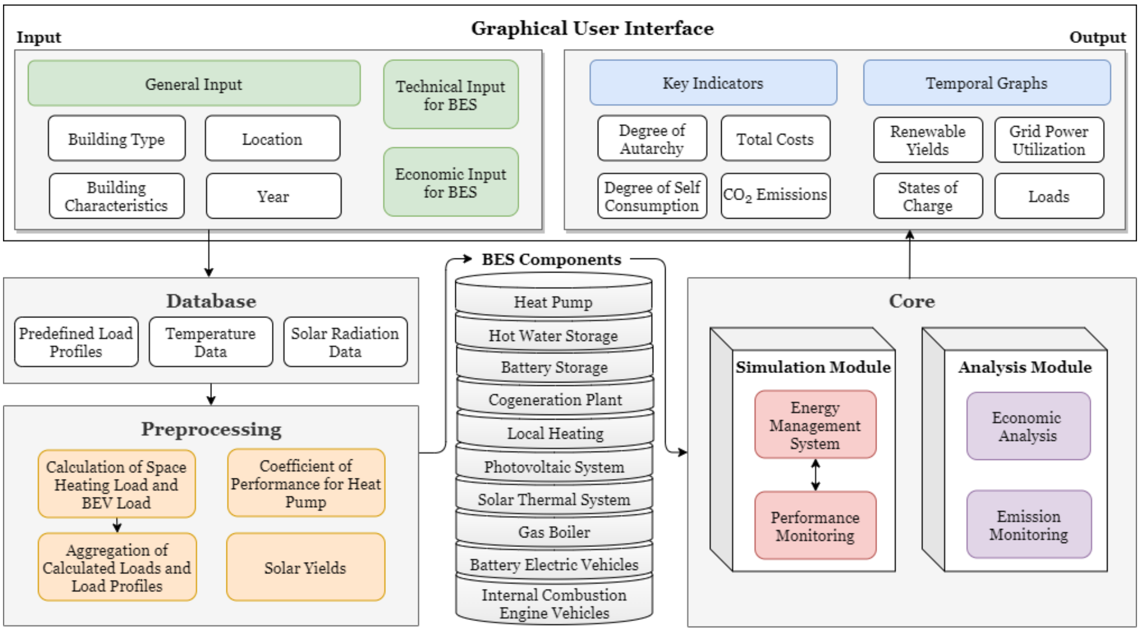

Figure 2: System Architecture of *NESSI*.

NESSI's overall MATLAB-based system architecture is presented in Figure 2. It includes the graphical user interface (GUI) structure, the underlying database with load profiles and weather time series, the eligible energy system components, and the simulation and analysis kernel. As demonstrated by the GUI structure, the user can customize the building type, location, characteristics, and base year. Based on these inputs, the pre-processing can calculate further input parameters such as the thermal load profile, solar yields, and the heat pump's coefficient of performance (COP). These input parameters and time series are, in turn, used for yearly energy system simulation in hourly resolution. The portfolio of energy technologies has been significantly expanded compared to the prior work in research article 2.1. *NESSI's* applicability and validity are demonstrated with a computational study. In this study, a detached family house and office building in Hanover are simulated based on real data, and subsequently, 26 energy system configurations are evaluated economically and ecologically. Moreover, the publication of 2.1

and a prior presentation of *NESSI* at the pre-ICIS SIG Green workshop in 2019 were conducted as evaluation steps.

2.3 Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Energy System Simulator NESSI

The research article 2.3 outlines the most mature version of *NESSI*. Through further iterations of [8]'s DSR process, significant enhancements have been incorporated into the overall DSS. *NESSI* has been completely migrated from MATLAB to the Python programming language, which has led to the deployment of *NESSI* as a web tool. The entire DSR-guided process is again presented using [9]'s publication scheme. *NESSI's* final software architecture is outlined in Figure 13.

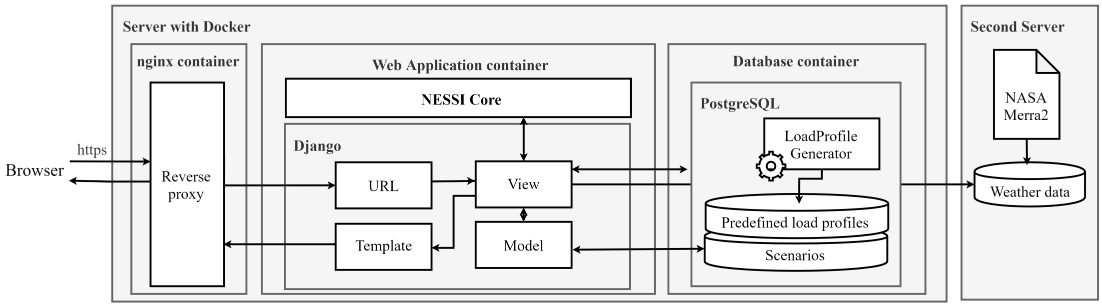

Figure 3: Final Software Architecture of *NESSI*.

Stakeholder, model, and system-oriented objectives were derived from a literature review of energy system models and a comparison with related computer tools. Current literature reviews (e.g., [11, 12]) confirm that open access release and out-of-the-box functionality are important tool characteristics. Based on an in-depth artifact description, the software architecture, the simulation procedure, including the rule-based energy flow model, and a demonstration of user flow are elaborated. Furthermore, measures for the evaluation (e.g., expert interviews, presentations on public events) of *NESSI* are presented, and their influence on the development process is disclosed.

As energy systems become more decentralized and the number of distributed energy resources (DERs) increases, microgrids have emerged. Microgrids represent a promising solution to operate many DERs with Information and Communication Technology (ICT) securely and efficiently in a network. In this context, academic literature is used to develop a morphological box in research article 2.4, which can be used to categorize microgrids.

2.4 Classification of Real-World Microgrids Based on a Morphological Analysis

Although a few research papers on MG design exist (e.g., [13, 14]), the literature regarding the classification of microgrids (MGs) and successfully implemented MG projects is limited. Based on methodologies of [15–17], a systematic and keyword-based literature search to identify MG design literature was conducted. After performing backward, forward, author, and *Google Scholar* similarity searches, 36 research articles were consolidated. The procedure of the subsequent morphological analysis is based on [18]. The resulting morphological box encompasses five layers, 18 dimensions, 60 characteristics. An in-depth description of the five layers, including an explanation of which characteristics were derived from which reference, is provided.

The morphological box is utilized to classify 30 real-world MG projects based on a literature search of real-world MGs. The 30 MG projects are divided into four campus-related, seven commercial- and industrial-related, eight community- and utility-related , three military, and eight remote MGs. The MG projects are spatially divided among the following continents: twelve in North America, three in South America, four in Asia, six in Europe, three in Africa, one in Australia, and one in Antarctica. Each MG was assigned a maximum of one characteristic in one dimension to adhere to the rationale of the morphological box. The morphological box can be utilized by stakeholders and decision-makers to either classify existing MGs or derive requirements for new MG projects.

In Energy Economics, one of the interesting issues is how the prices of renewable energy technologies evolve and market prices emerge. Based on a comprehensive dataset of photovoltaic system quotes, regression analyses are conducted that quantify the effects of various factors on rooftop PV system prices in research article 2.5.

2.5 Disentangle the Price Dispersion of Residential Solar Photovoltaic Systems: Evidence from Germany

Although Germany has a large and mature roof PV market compared to other European countries, it is challenging for many homeowners to evaluate whether they received a fair quote. There needs to be more price transparency in the market. Furthermore, from the perspective of policymakers, it is relevant to understand which factors must be addressed to establish reasonable PV system prices and thus

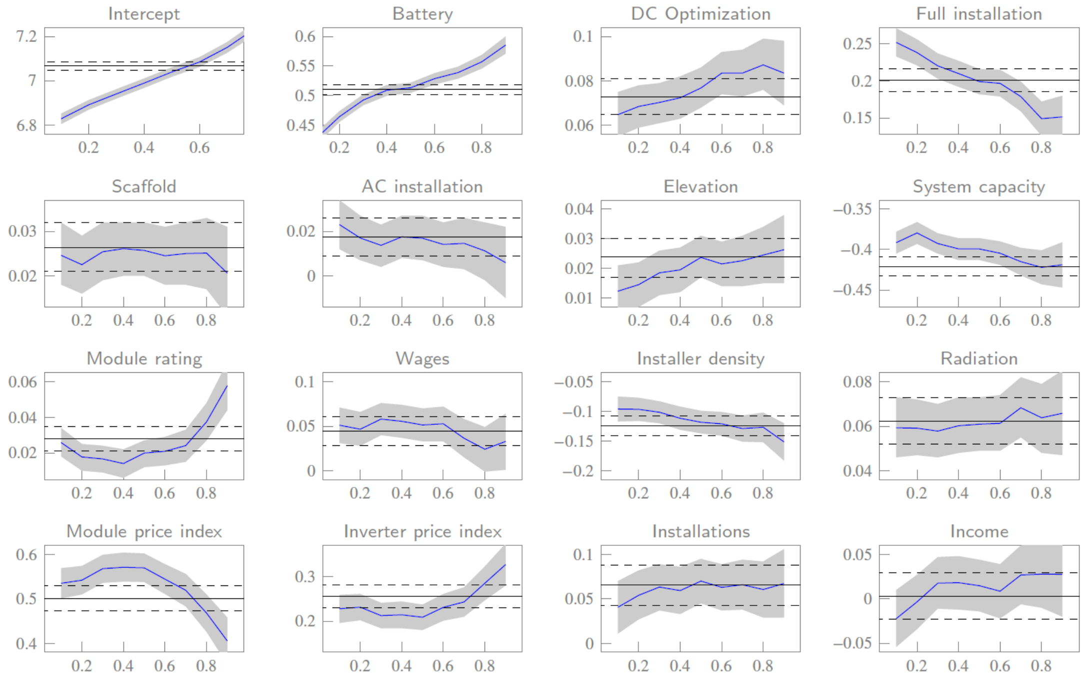

Figure 4: OLS (REF) estimates (continuous horizontal line) with respective CIs as dashed lines, quantile regression estimates (blue line), with respective 95 % CIs as shaded gray area.

amplify installations. Related studies on the decomposition of PV system prices have been conducted mainly in the United States (U.S.). [19] provided results on the deconstruction of solar PV pricing. [20] and [21] have investigated factors that affect low-priced PV systems, in particular, and the associated characteristics of those systems. Moreover, [22] and [23] have emphasized the importance of price transparency in residential PV markets and the effects of PV installer market concentration on system prices.

A web-mining approach collected 19, 208 PV system quotes from January 2011 to May 2022. The quotes comprised additional information about postal zip code, module and inverter characteristics, and further system attributes. This PV system quote dataset was enriched with features such as module efficiency or inverter power rating. The dataset is used to reveal geographic price heterogeneity in Germany in two-digit zip code resolution. Based on Hedonic price modeling, two linear ordinary least square (OLS) regression models are defined. One represents the reference model (REF), and the other incorporates geographically dependent variables as fixed effects. In addition, quantile regression is performed for five quantiles (PV price classes). Within the quantile regression, the effect sizes of 15 independent variables are quantified on five price quantiles. The effect sizes are shown in Figure 4 for each independent variable.

Shared Micromobility Usage and Safety

Profound changes are on the horizon in future urban transportation. Digital transformation and growing electric mobility have led to the widespread dissemination of shared mobility concepts in cities worldwide. Shared bicycles (bikes), electric scooters (e-scooters), and electric mopeds (e-mopeds) are the most common concepts. The emergence of these new transportation concepts poses significant challenges for cities. Adequate regulatory frameworks must be designed so that micromobility concepts can find a place in cities despite the scarcity of traffic space. Articles 3.1 and 3.2 analyze the temporal and spatial use of micromobility based on large location datasets. Article 3.3 investigates the causes of e-scooter accidents and derives implications for the ridership's safety.

3.1 A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage

Within nine months, around 4.2 million raw e-scooter trips were collected. Using comprehensive filter criteria related to travel time, average velocity, detour factor, and distance, the raw dataset was significantly reduced and consolidated to 1.25 million e-scooter trips. Four different trip types were identified by further filtering criteria related to haversine distance, energy consumption per trip, battery level deviation, and trip distance. User trips include one-way and round trips. Operator trips comprise charging and re-allocation trips.

The four trip types were examined for temporal usage patterns. Weekdays and weekend days were considered separately. One-way user trips increased in the morning between 7 and 9 a.m. on weekdays, suggesting work-related commuter trips. By far, the highest volume of user trips is in the afternoon on weekends. These weekend trips also had the longest average travel distance at about 2000 m. The temporal patterns revealed that charging trips predominantly occur in the evenings from 10 p.m. until late at night. Trips for re-allocating e-scooters were increasingly carried out between 7 and 9 a.m. and in the evening from 10 p.m. onwards.

The trip dataset was divided into origins and destinations to enrich the temporal analyses with geographic features. The five different land use types, residential,

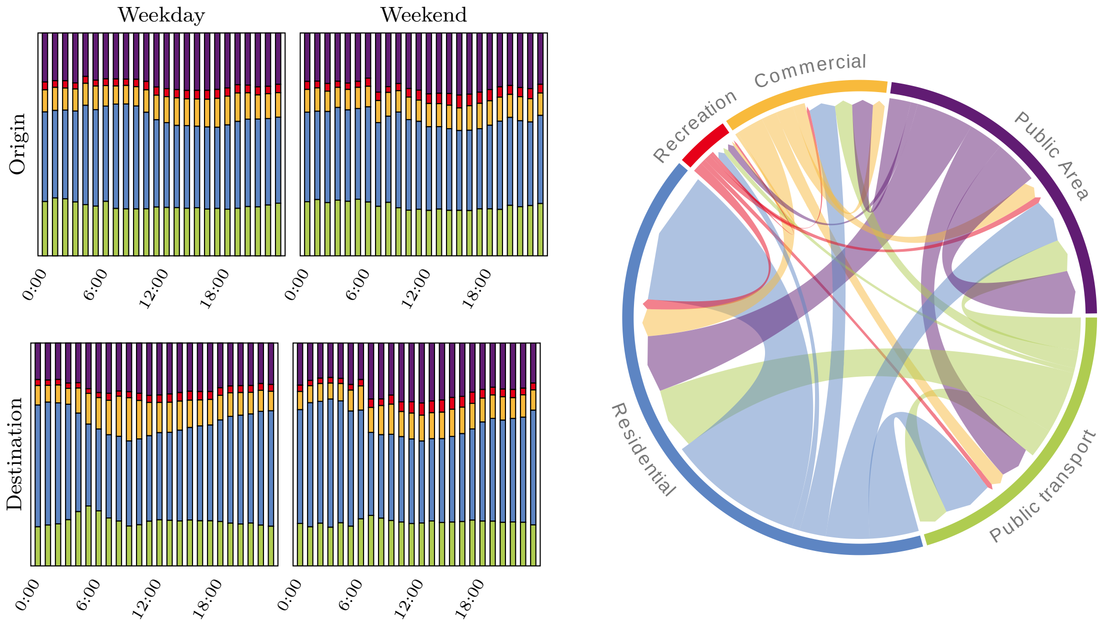

Figure 5: Temporal land use distribution of trip origins and destinations (left) and the corresponding connection in a chord diagram (right).

commercial, recreational, public, and public transport, were assigned to the origins and destinations. Figure 18 shows the temporal progression of origins and destinations per land use type. Moreover, origin-destination pairs are visualized as trip flows among land use types.
The influence of the built environment on origins and destinations is demonstrated using hierarchical and density-based spatial clustering with noise (HDBSCAN) algorithm. In addition, characteristic temporal usage patterns are revealed for various public transport-, sights- and commercial area-related points of interest (POI). The results on the spatiotemporal usage of e-scooters in Berlin can be used by urban and transportation planners and e-scooter operators for improved traffic flow planning and more efficient e-scooter deployment. The POI-resolved results enable urban planners in particular to take location-based measures.

3.2 Factors Influencing the Usage of Shared Micromobility: Implications from Berlin

This research article draws on a trip dataset of shared bicycles, e-scooters, and e-mopeds in Berlin from September 2019 to March 2022. It extended the single-mode investigation of research article 3.1 and increased the dataset's scope. The start and end points of the approximately 8.5 million micromobility trips were spatially

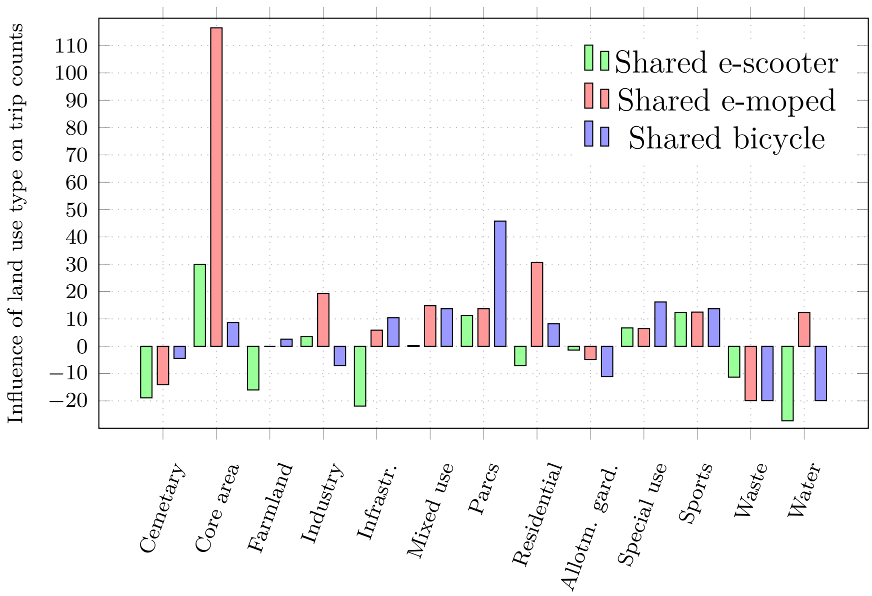

Figure 6: The percentage changes in trip counts associated with predominant land uses in a TAZ.

resolved to 542 traffic analysis zones (TAZs), creating a panel dataset. The Senate Department provides the TAZs for Urban Development, Building, and Living of Berlin. The TAZs have additional information about population density, tourists per day, gender, age distribution, and welfare recipients. Similar to research article 3.1, thirteen different land use types were used to geographically categorize trip origins and destinations. To quantify weather effects on micromobility trips, time series of air temperature, sunshine duration, humidity, precipitation, and wind speed from four weather stations were assigned to trips. Furthermore, temporal variables such as day of the week, weekends, time of day, Covid-19 lockdown periods, and dominant land use type per TAZ were added as categorical variables to the dataset.

Descriptive analysis of the dataset included temporal usage patterns and fleet size developments. The e-scooter-related temporal usage pattern of 3.1 was confirmed. Shared bicycles and e-mopeds showed a similar pattern. However, the trip volume of these two modes is significantly lower on weekdays between 10 a.m. and 4 p.m. Consideration of fleet size developments showed significant increases in vehicle numbers for all modes.

A negative binomial (NB) regression model was defined to quantify the influences of various factors on micromobility usage. The hourly trip volume of the three modes represents the variable to be described. The NB regression results indicated

that precipitation has the most negative effect of all weather variables. Covid-19 lockdown periods generally had a negative impact on trip volumes of the three modes, but e-mopeds were least affected. The effects of the thirteen land use types on mode usage are presented in Figure 6.
Core areas include commercial enterprises, central institutions of the economy, administration, and culture in TAZs. This land use type has a significantly positive effect on e-mopeds and e-scooters. In contrast, parks have the most positive effect on shared bicycle use. Overall, the results of this research article provide evidence that growing fleet sizes do not lead to proportionally more trips due to competitive effects. Effects associated with the thirteen land use types can enable operators for more efficient demand-based planning. Policymakers and operators can optimize sharing mobility services and facilitate evidence-based strategies for the spatial and temporal design of micromobility.

3.3 Web Content Mining Analysis of E-Scooter Crash Causes and Implications in Germany

The widespread use of e-scooters entails an increased risk of accidents and crashes. In addition to many clinical studies, one accident analysis with data sources like newspaper mining has been published in the U.S. [24]. Concerning Germany, the Federal Statistical Office has confirmed that the number of accidents involving e-scooters has doubled from 2020 to 2021 [25]. Due to the young history of e-scooters, few accessible data exist on e-scooter accident causes and outcomes in micromobility research. Therefore, a web content mining process (e.g., [26]) was developed to automatically collect and analyze $1,936$ police reports on e-scooter accidents. First, a systematic keyword-based literature search to consolidate the current state of research in accident analysis in micromobility was conducted.
The complete research design included conducting a systematic web content mining process (e.g., [26]) followed by sentiment and network analyses and visualization using a clustering algorithm. *Python*-based sentiment analysis was employed to assess objectivity in police reporting [27]. In comparison, network analysis was used to display graphical relationships from the most relevant keywords in the police reports. For this purpose, the open-source graph software *Gephi* was applied using *ForceAtlas2* and *Louvain* algorithms to create a network with communities [28, 29].
The resulting network with the 46 most important keywords is shown in Fig-

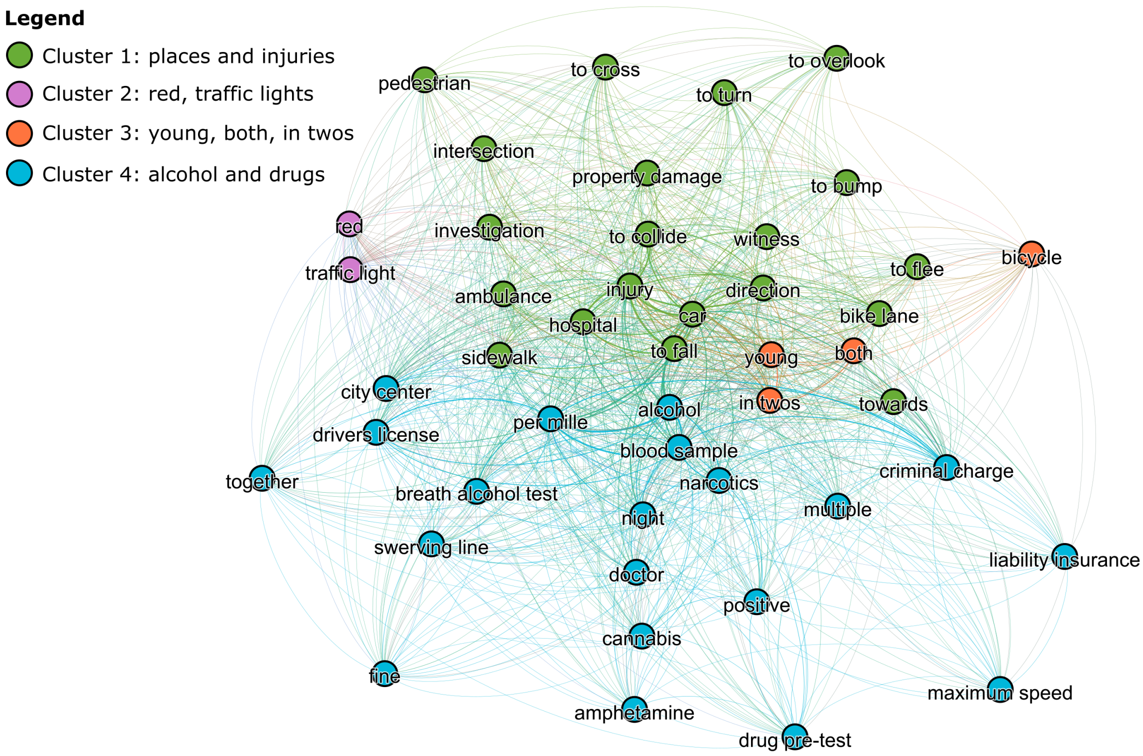

Figure 7: Network graph of 46 keywords and four communities visualized with *Gephi* using *ForceAtlas2* and Louvain algorithm [28].

ure 25. The four clusters were used to discuss accident causes and implications. In addition, five recommendations for improved safety for e-scooter ridership were proposed. Sentiment analysis confirmed objective reporting, as the polarity value was approaching zero.

4 User-centric Design, Development, and Evaluation of an Individual Digital Study Assistant for Higher Education Institutions

The number of lecturers and administrators has stagnated in recent years, while the student population has continued to grow and new academic programs have been developed [30]. Thus, a need for first, second, and third-level support for students at higher education institutions (HEIs) has arisen. This trend has intensified, especially during the Covid-19 pandemic. Consequently, characteristics such as intrinsic motivation, self-organization, and self-regulation have become even more significant for the successful course of studies [31].

However, acquiring these characteristics is perceived as demanding and challenging by students [32]. Additionally, [31] confirmed that a high degree of self-regulation

competencies positively influences HEI graduation. Starting from this problem, digital study assistants can address the lack of support options and thus enable students to succeed. Individual digital study assistants (IDSA) address these challenges with online, easy, ubiquitous, and automated access. Guided by Action Design Research, an IDSA that, e.g., improves students' self-regulation competencies, study goals achievement, and study organization were designed, developed, and evaluated in the field.

Based on 28 qualitative HEI expert interviews, a quantitative survey with 570 students, and a literature review, we first derive general IDSA requirements. User-centered, we then develop and evaluate our IDSA prototype tested by more than 1000 students. It, e.g., recommends lectures based on individual interests and competencies, offers matches with other students, or gives feedback about learning behavior strengths and weaknesses and can partly replace or supplement human first-level support. The IDSA requirements offer HEI administrative and lecturers practical knowledge and recommendations, support IDSA theory building, and reveal further research needs.

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Overview of Publications and Task Allocations

As summarized in Table 2, the underlying publications of this dissertation are classified based on the metrics of *German Academic Association for Business Research* (VHB) (e.g., [33]), the impact factor (IF), and *SCImago Journal & Country Ranks* (SJR) in 2021 (e.g., [34]). SJR metrics divide journals into quartiles in their associated research areas. If a journal is rated $Q1$, it belongs to the top 25% of all journals in that research area [35]. IF data is based on metrics provided by the journals' homepages. In general, the IF measures the average citations received in a given year by articles published in a defined previous period. Journals from *Elsevier* indicate the two-year IF. It is defined as follows: "The Impact Factor measures the average number of citations received in a particular year by papers published in the journal during the two preceding years" [36]. All published and submitted research articles of this dissertation were and are subject to peer-review processes. Additionally, for each article, the task allocation of authors is explained in detail.

Tobias Kraschewski and I have published the completed research paper *Decision Support for Optimal Investments in Building Energy Systems* on 25^{th} Americas' Conference on Information Systems in Cancun, Mexico. It represents one of North America's leading and established annual conferences on IS research. We have equally elaborated the idea and storyline of the article. I wrote large parts of the Introduction, Research Background and Design, and Artifact Description. Furthermore, I helped to design the Case Study and discuss the results. Tobias Kraschewski wrote significant parts of the Artifact Description, the Case Study, and the result interpretation. Michael H. Breitner has sharpened the article through discussion contributions and feedback. I presented our research article on AMCIS in August 2019 in Cancun, Mexico.

Tobias Kraschewski, Sarah Eckhoff, Michael H. Breitner, and I have published the completed research article *Transformation to Sustainable Building Energy Systems: A Decision Support System* on the 41^{st} International Conference on Information Systems (ICIS) which was conducted online. According to the Association for Information Systems (AIS) the ICIS is the most prestigious IS conference worldwide. All authors contributed equally to the idea and storyline of the research article. I wrote large parts of the Introduction, Theoretical Background and Related Research, and Research Design. Additionally, I helped to conceptualize the Computational Study and results discussion. Tobias Kraschewski had the overall project lead and wrote significant parts of the DSS Description, Computational Study, and Discussion and Recommendations. Sarah Eckhoff was primarily responsible for the DSS development. She wrote the DSS Description and contributed to the Computational Study, Discussion, and Recommendations. Michael H. Breitner was a discussant and contributed to the final research article. Tobias Kraschewski presented our research article virtually on 41^{st} ICIS in 2020.

The completed research paper *Classification of Real-World Microgrids Based on a Morphological Analysis* was published at the 27^{th} AMCIS in Montreal, Canada, by Jana Gerlach, Sarah Eckhoff, Oliver Werth, Tobias Kraschewski, Michael H. Breitner and myself. Jana Gerlach and Sarah Eckhoff wrote the main parts of the paper, conducted the literature searches, and categorized real-world MG projects. Oliver Werth wrote the methodology section. I helped conceptualize the morphological box's layers, dimensions, and characteristics. All authors contributed to the discussion of results and overall editing. Michael H. Breitner was a discussant and contributed to the article's final version. Jana Gerlach presented our article virtually at the 27^{th} AMCIS in 2021.

Maximilian Heumann, Tobias Kraschewski, Lukas Tilch, Michael H. Breitner, and I have published the full-length article *A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage* in the journal Sustainability in November 2021. The journal has a five-year IF of 4.09 [37]. According to SJR metrics, the journal is ranked as $Q1$ in Geography, Planning, and Development, and $Q2$ in Environmental Sciences [38]. The authors' contributions can be found in the publication. Specifically, I wrote large parts of the Introduction, conducted the Literature Review, developed and supported the data filtering, and conceptualized and interpreted temporal and spatial analyses. Michael H. Breitner was a discussant and contributed to the final research article.

Maximilian Heumann, Tobias Kraschewski, Oliver Prahlow, Jan Rehse, Christian Kiehne, Michael H. Breitner, and I have published the full-length article *Web Content Mining Analysis of E-Scooter Crash Causes and Implications in Germany* in the journal Accident Analysis & Prevention in December 2022. This journal has a two-year IF of 6.38 [39]. According to SJR, it is among the best five journals in the subject area of Safety, Risk, Reliability, and Quality. Moreover, it ranks as the second-best journal worldwide in the subject area of Human Factors and Ergonomics [40]. As the first author, I conceptualized the idea of the article and performed the overall project supervision. I wrote large parts of the Introduction, Data and Research Methods, Discussion, and Results. Maximilian Heumann and Tobias Kraschewski supervised the data analyses and contributed to the result interpretation and editing. Oliver Prahlow wrote large parts of the Literature Review. Jan Rehse wrote large parts of the Discussion and contributed to the visualization of results. Christian Kiehne contributed to the data collection. Michael H. Breitner was a discussant and contributed to the final research article.

Furthermore, Maximilian Heumann, Tobias Kraschewski, Lukas Tilch, Michael H. Breitner, and I have submitted the article *Factors influencing the usage of shared micromobility: Implications from Berlin* to the *Journal of Transport Geography* with a current two-year IF of 5.89 [41]. This article is currently under review for the second time after major revisions. SJR metrics indicate that it is a Q1 journal in the areas of Transportation and Environmental Sciences [42]. I contributed mainly to the Data and Methodological Approach and Results and Discussion in writing the paper. Maximilian Heumann supervised the project and wrote the main parts of the paper. Tobias Kraschewski contributed to the Data and Methodological Approach and wrote parts of the Discussion and Results. Lukas Tilch contributed to the data collection. Michael H. Breitner was a discussant and contributed to the final research article.

Christin Karrenbauer, Claudia M. König, Michael H. Breitner, and I have written the full-length article *User-centric design, development, and evaluation of an individual digital study assistant for higher education institutions* and submitted it to the journal *Educational Technology Research and Development*. It has a current IF of 5.58 [43]. According to SJR metrics, it is a Q1 journal in the area of Education [44]. The article was under review at the time of submission of this dissertation. The article has since been accepted and has been published since June 2023. I was primarily responsible for the Prototype Development and wrote large parts of the Discussion, Implications, and Recommendations. Christin Karrenbauer supervised the project and wrote large parts of the Introduction, Results and Findings, and Conclusions. Claudia M. König wrote significant parts of the Theoretical Background and Research Design and Methods. Michael H. Breitner was a discussant and contributed to the final research article.

Tobias Kraschewski, Maximilian Heumann, Michael H. Breitner, and I have submitted the full-length article *Disentangle Influencing Factors of Residential Photovoltaic Price Dispersion* to the journal Energy Economics with a current two-year IF of 9.25 [45]. According to SJR, it is ranked as $Q1$ journal in Economics and Econometrics, and Energy [46]. I wrote parts of the Results, and Discussion, Introduction and contributed to the data processing and analyses. Tobias Kraschewski supervised the project and wrote the main parts of the paper. Maximilian Heumann also wrote parts of the Discussion and Results and contributed to the data collection and processing. Michael H. Breitner was a discussant and contributed to the final research article.

Sarah Eckhoff, Maria C. G. Hart, Tobias Kraschewski, Maximilian Heumann, Michael H. Breitner, and I have submitted the full-length article *Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Energy System Simulator NESSI* to the journal *Building and Environment*. It has a current two-year IF of 7.09 [47]. SJR metrics rank this journal as $Q1$ in areas Building and Construction and Environmental Engineering [48]. I wrote large parts of the Evaluation and contributed to the Introduction and Literature Review. Sarah Eckhoff had the overall project lead and wrote large parts of the Artifact Description and Research Design. Maria C. G. Hart wrote large parts of the Introduction, Literature Review, and Discussion. Tobias Kraschewski and Maximilian Heumann supervised the overall article and contributed to some sections. Michael H. Breitner was a discussant and contributed to the final research article.

Table 2: Overview of Publications and Submissions Under Review.

#	Status	Title	Authors	Journal & Conference	VHB[1]	IF[2]	Appendix
9	04/2023	Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Energy System Simulator NESSI	Eckhoff, S., Hart, M.C.G., Brauner, T., Kraschewski, T., Heumann, M., Breitner, M.H.	Building and Environment	-	7.09	A.9
8	04/2023	Disentangle the Price Dispersion of Residential Solar Photovoltaic Systems: Evidence from Germany	Kraschewski, T., Brauner, T., Heumann, M., Breitner, M.H.	Energy Economics	B	9.25	A.8
7	06/2023	User-centric design, development, and evaluation of an individual digital study assistant for higher education institutions	Karrenbauer, C.; Brauner, T.; König, C.M.; Breitner, M.H.	Educational Technology Research and Development	-	5.58	A.7
6	Under Review	Factors influencing the usage of shared micromobility: Implications from Berlin	Heumann, M.; Brauner, T.; Kraschewski, T.; Tilch, L.; Breitner, M.H.	Journal of Transport Geography	-	5.89	A.6
5	12/2022	Web Content Mining Analysis of E-Scooter Crash Causes and Implications in Germany	Brauner, T.; Heumann, M.; Kraschewski, T.; Rehse, J.; Prahlow, O.; Kiehne, C.; Breitner, M.H.	Accident Analysis & Prevention	-	6.38	A.5
4	11/2021	A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage	Heumann, M.; Kraschewski T.; Brauner, T.; Tilch L.; Breitner, M.H.	Sustainability	C	3.89	A.4
3	08/2021	Classification of Real-World Microgrids Based on a Morphological Analysis	Gerlach, J.; Eckhoff S.; Werth O.; Kraschewski T.; Brauner T.; Breitner M. H.	Proceedings of the 27th Americas Conference on Information Systems (AMCIS) 2021, Montreal (Canada)	D	-	A.3
2	12/2020	Transformation to Sustainable Building Energy Systems: A Decision Support System	Kraschewski, T.; Brauner, T.; Eckhoff, S.; Breitner, M.H.	Proceedings of the 41st International Conference on Information Systems (ICIS) 2021, Hyderabad (India)	A	-	A.2
1	08/2019	Decision Support for Optimal Investments in Building Energy Systems	Brauner, T; Kraschewski, T.	Proceedings of the 25th Americas Conference on Information Systems (AMCIS) 2019, Cancun (Mexico)	D		A.1

[1] based on [33] [2] based on journals' homepages and [36]

1 Introduction

1.1 Research Motivation, Problems and Questions

This dissertation is divided into three domains. Five articles can be assigned to the topics of Decision Support Systems (DSS), Energy Informatics (EI), and Energy Economics. Three articles investigate the temporal and spatial usage and safety of Shared Micromobility in urban areas. One research article contributes to the area of digital study assistance. In the following, the research motivation of the domains and the underlying problems are presented.

Mitigating the effects of climate change represents one of the most significant challenges for the twenty-first century. Global carbon dioxide (CO_2) emissions must be drastically reduced to achieve international climate goals. Significant technological transformations are on the horizon for various sectors such as industry, transport, commerce, trade and services, and households. Industry, commerce, and households operate, work, and live in buildings. According to the International Energy Agency (IEA), the energy supply of buildings accounts for 30% of global energy consumption. Moreover, building operations account for 27% of total energy sector emissions [1]. The transformation of the energy systems in buildings thus represents an essential lever for global CO_2 emission reduction. Many stakeholders, such as residential and commercial homeowners, house communities, or municipalities, face the complex task of transforming their buildings towards an emission-free energy supply. Constantly advancing energy technologies, changing regulatory frameworks, and energy prices impede investment decisions for stakeholders. Here, Information Systems (IS) research on Decision Support Systems (DSS) can provide relevant solutions so stakeholders can make data-driven and appropriate decisions. Several established IS scholars have challenged the IS discipline for over a decade to disengage from exclusively theory-building research and open up to relevant solutions for global societal problems [4, 49]. In particular, due to the long tradition of Design Science Research (DSR) in the IS discipline, it can provide solution-oriented and impactful contributions to tackling the problem of buildings' transformation towards emission-free energy supply. This dissertation addresses this problem and elaborates on developing a DSS to transform buildings based on three research articles.

The increasing decentralization through spatially distributed energy resources, particularly renewable energies, poses a significant challenge for the energy sector. Regarding this problem, microgrids (MGs) have emerged to control a large number of distributed energy resources efficiently [14]. Despite some implemented MG projects, MGs and guidelines for upcoming projects need to be more systematized. This thesis addresses this problem with a research article that derives a morphological box from academic literature to categorize MGs.

Renewable energies must be expanded on a large scale to achieve international climate goals. Among other technologies, expanding rooftop photovoltaic (PV) systems represent an important pillar in providing clean energy. While Germany already has the highest PV system capacity in Europe with 58.4 GW, the potential of this technology is estimated at 208 GW [50]. The expansion of rooftop PV systems has decreased considerably in Germany in recent years. In this context, the spatial price heterogeneity of PV system quotes can be an issue. Market players lack price transparency impeding investment decisions. This dissertation addresses this problem and analyzes the influence of different factors on PV system prices.

The second research domain represents the spatial and temporal usage and safety of micromobility. While shared bicycle (bike) concepts have existed for longer, shared free-floating e-scooter systems emerged in 2017 in the U.S. Additionally, e-mopeds that go faster than 20 km/h are also provided. The rapid introduction and widespread adoption of these micromobility concepts, especially e-scooters, have posed significant challenges to cities worldwide. Primarily, micromobility concepts are intended for flexible, emission-free trips that can solve the first- and last-mile problem, especially in the urban environment. However, these positive aspects are overshadowed by misuse, vandalism, congested sidewalks and bike lanes, and other harmful aspects. Traffic and city planners and city authorities can advance the development of suitable measures if there are data-based analyzes of the temporal and spatial use of micromobility concepts. This dissertation addresses these issues with three research articles. Two of them provide in-depth temporal and spatial analyzes of the use of micromobility in Berlin. The third research article examines the causes and implications of e-scooter accidents in Germany.

The third domain of this dissertation deals with the digital and individual assistance of students at higher education institutions (HEIs). Increasing student numbers and stagnant staff at the HEIs are weakening individual student support. Inexperienced students, in particular, are challenged to learn essential skills such as self-regulation, organization, and intrinsic motivation. This is where IS research ties in and can reach many students using digital assistants. This dissertation provides a research article that uses the principles of Action Design Research (ADR) to determine the requirements for an individual digital study assistant. Additionally, a prototype was developed that was tested by students on three HEIs. Table 3 summarizes the investigated topics, addressed stakeholders, and research questions of this dissertation's underlying nine research articles.

1.2 Research Methodologies

The thematic diversity of the articles in this dissertation is also reflected in the research methodologies employed. The following summarizes the most relevant research methods and refers to pertinent literature. Furthermore, reference is made to the articles in which the methods were applied.

Design Science Research and Qualitative Methods

The completed research articles in Sections 2.1 to 2.3 address real-world problems using the development of a DSS. The DSS and Design Science Research (DSR) domains have always been closely intertwined in the IS discipline. DSR was partly initiated by the work of [7] and represents a problem-oriented and design-open research methodology. Creating an IT artifact appropriate to the problem through a rigorous scientific-oriented approach constitutes the core idea of DSR. IT artifacts often represent the coupling point between the DSR and DSS domains. [51] formulated the following definition for DSS: *" ... interactive computer-based system or subsystem intended to help decision-makers use communication technologies, data, documents, knowledge, and/or models to identify and solve problems, complete decision process tasks, and make decisions."* Moreover, to strengthen the relevance and quality of DSS, DSR represents the most important strategy to tackle real-world problems with scientifically validated IT artifacts [52].

The research articles in Sections 2.1 to 2.3 are based on the three-cycle approach of [7] and the adapted DSR framework of [8]. The two research articles in Sections 2.2 and 2.3, in particular, are structured according to [9]'s seven-step DSR publication scheme. According to this scheme, the problem statement and its relevance are outlined first. The literature review addresses prior work including empirical studies, findings, and artifacts for related problems. In the methodology part, reference is made to the specific DSR approach (e.g., [8, 10]). This is followed by a consistent and accurate artifact description, which is the article's main body. Subsequently, an evaluation demonstrates the artifact's validity, utility, quality, and efficacy. The demonstration results are interpreted, and the contributions and implications are

Table 3: Topics, addressed stakeholders, and investigated research questions.

Topic	**Stakeholders**	**Research Questions**
Decision Support for Optimal Investments in Building Energy Systems	Residential prosumers	*RQ: "How can incremental investments optimally enhance building energy systems' efficiency?"*
Transformation to Sustainable Building Energy Systems: A Decision Support System	Residential, commercial building owners	*RQ: "How can a DSS be developed to visualize and simulate the environmental and financial impact of different building energy systems configurations to raise awareness and encourage actions by stakeholders?"*
Accessible Decision Support for Sustainable Buildings and Neighborhoods: Energy System Simulation Tool *NESSI*	Residential, commercial building owners, Energy consultants, Municipalities	Comprehensive DSS presentation
Classification of Real-World Microgrids Based on a Morphological Analysis	Microgrid project stakeholders	*RQ1: "Which MG design options can be extracted from literature using a morphological analysis?"* *RQ2: "How can real-world MGs be classified using the morphological box and which implications and recommendations for future research and practice can be derived?"*
Disentangle the Price Dispersion of Residential Solar Photovoltaic Systems: Evidence from Germany	Photovoltaic market players, Residential building owners	*RQ1: "Which factors affect rooftop solar photovoltaic system prices in Germany"* *RQ2: "What factors are particularly price-determining for system quantiles?"*
A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage	Urban and traffic planners, Micromobility operators	*RQ1: "How are shared e-scooters used in space and time in Berlin?"* *RQ2: "How can cluster and land use type analyses contribute to an improved understanding of shared e-scooter usage?"*
Factors influencing the usage of shared micromobility: Implications from Berlin	Urban and traffic planners, Micromobility operators	*RQ: "How is shared e-scooter, bicycle, and e-moped use affected by spatiotemporal weather, COVID-19, demographic, and fleet size-related variables in Berlin?"*
Web content mining analysis of e-scooter crash causes and implications in Germany	Micromobility operators, Traffic safety authorities	*RQ: "What are relevant causes and implications associated with e-scooter crashes in Germany?"*
User-centric Design, Development, and Evaluation of an Individual Digital Study Assistant for Higher Education Institutions	HEI students, HEI authorities (lecturers, organizational leaders)	*RQ: "What requirements guide a user-centric design and development of an IDSA?"*

highlighted. The core ideas and contributions are again summarized in the final part of the conclusions. The actions and steps taken are described in detail in the corresponding research articles [53–55].
Based on design research, [56] proposed the adapted methodology Action Design Research (ADR) in 2011, which addresses the development of IT artifacts in organizational contexts. [56] argued that the relevance and usefulness of IT artifacts in organizations often diminished due to the focus on technical rigor. The core idea of ADR is that designs of relevant IT artifacts arise from the interplay of theory, organizational context, and practical use. The ADR Framework includes a four-stage approach with seven principles. The ADR process was followed to develop a digital study assistant in [57]. Three universities represented the organizational context. A qualitative method in the sense of expert interviews was carried out in [57] and [55].

Literature Reviews

Literature Reviews were conducted to varying extents in many of the research articles in this dissertation. Several inevitable frameworks for conducting literature searches and reviews have been established in IS research over the past two decades. For this dissertation, the guidelines of [15], [16], and [17] are particularly relevant. The literature reviews performed on all articles generally aimed to reflect the current state of research. Due to the constantly growing body of research and the high frequency of publications in certain fields, the reflection of a research state is only a brief overview. Since none of the research articles in this dissertation carried a review focus only, the literature reviews were conducted in varying degrees of depth and detail. In [58], a systematic keyword-based review was conducted according to the guidelines of [15–17]. In [59] an extensive but unguided literature search was conducted in the dynamic micromobility research field. In contrast, the literature reviews in the DSR-guided articles (e.g., [53–55]) aimed to present the related DSS.

Quantitative Methods and Data Science Techniques

In many research articles, quantitative methods were applied to different data foundations. Before using quantitative methods for data analysis, the articles (e.g., [59–61]) transparently outlined the steps of data acquisition to data analysis in the form of data pipelines. Descriptive statistical methods, such as mean, median, quantiles, normalization, and additional metrics, were used to present the datasets comprehensibly. In two articles (e.g., [61, 62]), regression models were used to investigate the effect of exogenous variables on an endogenous one. In [61], a hedonic price model and quantile regression were applied to estimate the influences of factors on the price of photovoltaic systems. A negative binomial regression model was defined in [62] to determine the effects of weather and other factors on micromobility trip volumes. Regarding data science techniques, clustering algorithms (e.g., [59, 60]), cosine similarity ([59]), sentiment analysis, and network graph analysis ([60]) were employed.

1.3 Structure

This dissertation is divided into three research streams as highlighted by Table 3. First, the DSS-, EI-, and Energy Economics-related research stream and associated publications are presented. While Sections 2.4 and 2.5 each address individual publications, Sections 2.1 to 2.3 aggregate multiple research articles on the DSS *NESSI*. Then, three contributions to shared micromobility research are presented in each of the Subsections 3.1 to 3.3. The research article on individual digital study assistants is summarized in Section 4. Finally, a final appraisal, critical reflection of the research work, and outlook are presented in Section 5.

2 Decision Support Systems, Energy Informatics, and Energy Economics

This section encompasses the development and evolution of the DSS *NESSI* from 2018 to 2023 and represents the first pillar of this dissertation. The working title of the DSS stems from the original name *Nano Energy System Simulation*. *NESSI's* original scope was focused on individual building energy systems. This premise changed from 2020, and *NESSI's* functionalities were also to be transferable to quarters. The working title was nevertheless retained to establish the relationship of new research articles to previously published work. First, the initial scientific publication on the DSS approach and application by [53] in Section 2.1 is presented. Then, the evolution of the DSS approach to the artifact *NESSI* is summarized in Section 2.2. Finally, the most mature version of *NESSI* is outlined in Section 2.3, which has been extensively evaluated with various stakeholders.

The development project was carried out in the DSR framework and methodologically follows several DSR guidelines [7–10, 63]. Overarching, the motivational background of the articles in 2.1 to 2.3 derives from various (Green) IS calls and prior work. For instance, [4] called on the IS community in 2010 to leverage the transformative power of IS research in environmental sustainability. [5] has emphasized the importance of solution-oriented IS artifacts that address the most pressing global challenges. These calls from the IS discipline are reflected in the multi-year development of the DSS *NESSI*.

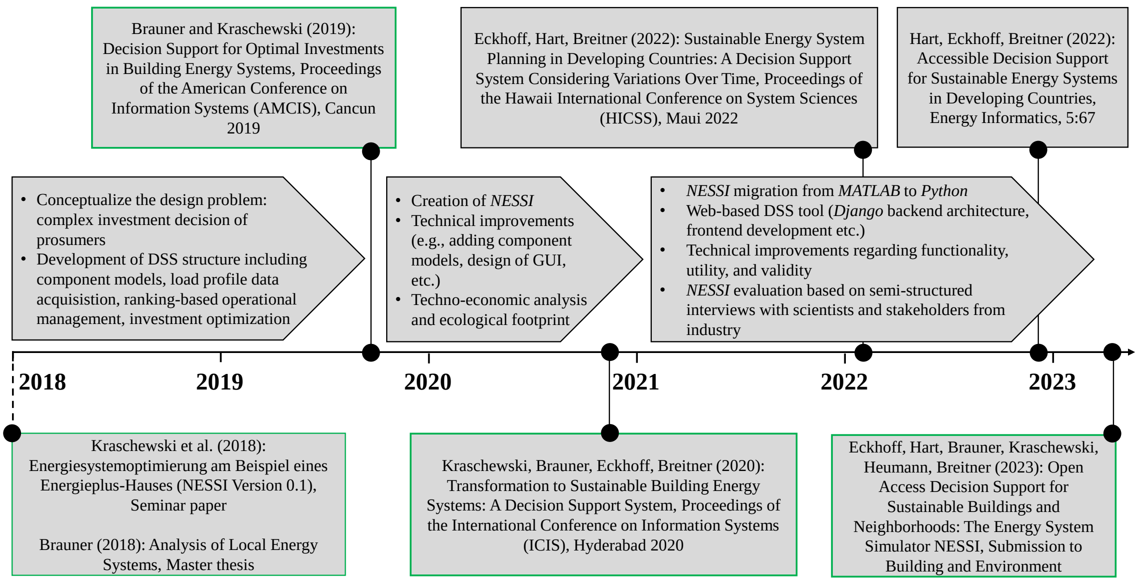


Figure 8: Milestones of the DSR project *NESSI*.

Figure 8 shows the most critical development steps and scientific publications on *NESSI* on a timeline. The scientific works on *NESSI* that are part of this dissertation are marked in green. The development began in 2018 and was primarily initiated by [64]'s seminar work and complemented by the master thesis of [65]. Due to several years of development and numerous technical changes, only selected essential milestones of the development are summarized. The three research articles (2.1 - 2.3) are summarized chronologically below and, in addition, their influence on DSS development is reflected. Then, two research articles (2.4 and 2.5) are presented, which are in the areas of Energy Informatics and Energy Economics.

2.1 Decision Support for Optimal Investments in Building Energy Systems

The following is a summary of the article *Decision Support for Optimal Investments in Building Energy Systems* (Appendix A.1) by Tim Brauner and Tobias Kraschewski [53]. The article was published in the Proceedings of the American Conference on Information Systems (AMCIS) in 2019. This article was presented as part of the Green IS and Sustainability conference track.

2.1.1 Summary of contents

The *Renewable Energy Sources Act* (EEG) introduced a 20-year guaranteed feed-in tariff for rooftop photovoltaic (PV) systems in 2000 in Germany. It guaranteed small to medium-sized PV systems up to 5 MW p, which were installed before 2000, a remuneration rate of 0.506 €/(kW h). Thus, the EEG led to enormous annual deployment rates until 2012. In contrast to 2000, PV systems up to 40 MW p have only received a remuneration rate of 0.110 €/(kW h) in February 2019. As outlined by [66], the remuneration rate has decreased significantly over the last ten years. The levelized cost of electricity (LCOE) of PV systems has already been below the ones from fossil energy carriers since 2012. Thereby, the point of grid parity occurred.

Since about 2012, the cost of electricity from the grid has overtaken the feed-in tariffs for rooftop PV systems. Therefore, the degree of self-consumption shifted to the spotlight. Many studies (e.g., [67, 68]) have investigated the technical interaction between PV systems and other system components like heat pumps, electric vehicles, and small co-generation plants. At the time, the authors missed the incorporation of economic metrics and analyses in these studies. In 2016, [6] defined households that consume energy and generate and feed it into the grid as prosumers. We identified two critical issues for prosumers: (i) rooftop PV systems installed before 2000 will fall out of the remuneration scheme, and the question arises about the further operation and possibly the coupling with other components. (ii) a large share of system owners must increase the self-consumption of the PV system, and the question arises as to how this goal can be achieved efficiently from an economic point of view. With this technical and economic background, we posed the following research question:

How can incremental investments optimally enhance building energy systems' *efficiency?*

To address this research question, we have developed a MATLAB-based DSS to monitor and optimize building energy systems' performance efficiency.

Research Background and Research Design

Our research belongs to the fields of energy system simulation and optimization. Many reviews and studies (e.g., [69–72]) confirm the wide range of software tools. Therefore, we compared the two most common software tools and our DSS. [69] and [71] emphasized the hybrid optimization model for electric renewables (*HOMER*) software. Based on input parameters like load demand, economic and technical component details, and emission data, *HOMER* can determine the optimal sizing of components while minimizing net costs. Moreover, [70] and [71] highlighted the hybrid system simulation software (*HYBRID*) based on precise time series to predict the performance of hybrid energy systems and further provide economic analysis. Hybrid energy systems encompass renewable energy sources and fossil energy generation. *HOMER* and *HYBRID* represent powerful numerical tools that provide comprehensive technical and economic analysis. At the time of our comparison, *HOMER* and *HYBRID* were primarily for engineers that create and plan microgrids with multiple renewable energy and fossil sources and consumers. *HOMER* and *HYBRID* are commercial software tools designed for researchers and engineers. The operational management and sizing of components can be optimized. These premises represent a fundamental difference to our DSS. Regarding our research background and design, we have drawn on the fundamental DSR principles of [7] and [8]. We chose this design-oriented research approach because we aimed to solve prosumer decision-making problems using an IS artifact. Since we intended our IS artifact to contribute to environmental sustainability, we located our motivational background in Green IS and EI [73, 74].

DSS Structure, Operational Management, Performance Monitoring, and Investment Evaluation

Our DSS for prosumers is composed of four essential parts. First, we have incorporated electrical and thermal load profile data of [75] to enable users to model their load profile. In the second step, we have modeled relevant energy system components for prosumers. Each component is defined by the technical parameters in Table 4. Third, we established a rule-based (discrete) operational management model that controls the energy flows in the building energy system at hourly time resolution. The energy system and its components are simulated for a year, and the thermal and electrical load is covered. In Figure 9, we showed the discrete operational management, including electrical and thermal energy flows.

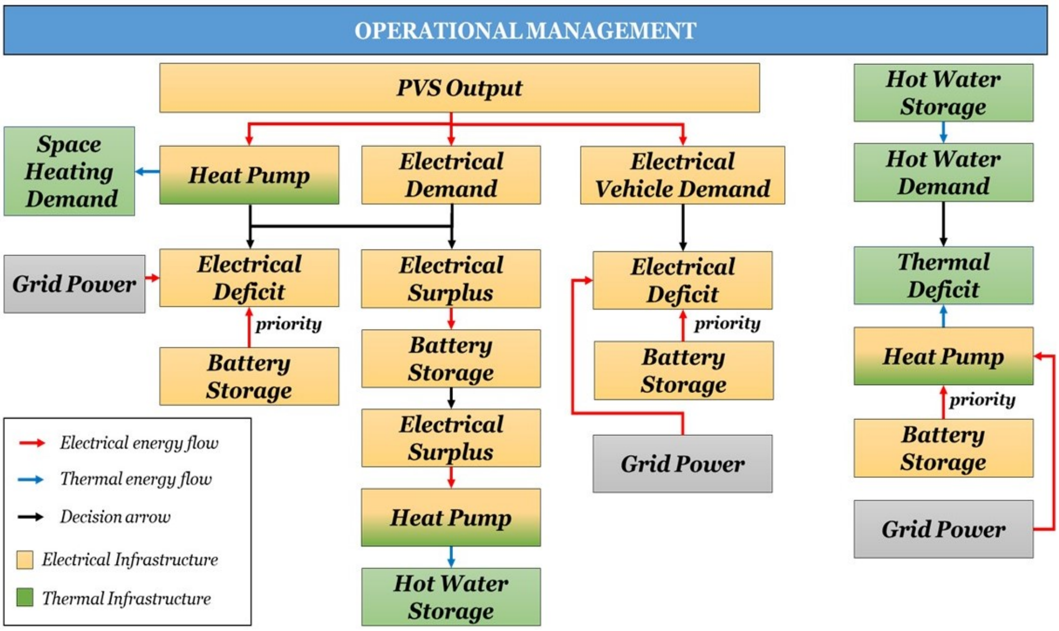


Figure 9: Operational management and energy flow priorities in the BES.

The operational management relied on three fundamental premises, which are listed below:

- Electrical and thermal loads are covered in each hour of the simulation using PVS yield, energy storages (BS and WS), and grid power.
- The energy storage's state of charge (SOC) cannot exceed maximum or minimum capacity. Moreover, energy storage (dis-) charge is restricted to maximum and minimum discharge rates.
- The operational management maximizes the degree of self-consumption by primarily utilizing PVS yield to cover load and charge storage. The electrical surplus is fed into the grid when the load is covered, and the storage units are fully charged.

Furthermore, the operational management tracked the hourly degree of self-consumption (DSC) and degree of autarchy (DoA). The DSC is defined by the sum of PVS yield that has been internally consumed P_{PVS}^{IC} and charged into storage $P_{Storage}^{Ch.}$ divided by the sum of total PVS yield P_{PVS} in Equation (1). In contrast, the DoA relates the sum of the internally consumed PVS share P_{PVS}^{IC} and the discharged energy of the storage units $P_{Storage}^{Disch.}$ to the total consumption of the household D_{Total} (cf. Equation (2)). Additionally, we used the total demand of grid power, total feed-in power, and energy losses as performance indicators.

$$DSC = \frac{\sum P_{PVS}^{IC} + \sum P_{Storage}^{Ch.}}{\sum P_{PVS}} \tag{1}$$

$$DoA = \frac{\sum P_{PVS}^{IC} + P_{Storage}^{Disch.}}{D_{Total}} \tag{2}$$

Considering our research question, the prosumer could invest in a PVS, battery, or hot water storage. An incremental investment can increase the PVS, BS, or WS's capacity (nominal power). To quantify the economic effect of incremental investments in the building energy system, we defined Equation (3). The energy system changed by the investment is compared with the previous energy system. Equation (3) was used to estimate how much cost reduction CR_t^I is obtained compared to the previous year. There are two cost reduction options: (i) lowering the grid power supply by using self-generated power can reduce costs. However, the self-generated and consumed energy can no longer be fed in via remuneration, so it must be subtracted as a lost opportunity. (ii) additional income can be generated by increasing the energy fed into the grid. If a prosumer cannot access a remuneration scheme, the electrical surplus can be sold at the market price $\tilde{p}_{EEX}$ on the electricity exchange. Thereby, $\tilde{p}_{EEX}$ substitutes $\tilde{p}_{Feed-in}$ in Equation (3).

$$CR_t^I = [(P_{t-1}^{Grid} - P_t^{Grid}) * (\tilde{p}_{Grid} - \tilde{p}_{Feed-in})] + [(P_t^{Feed-in} - P_{t-1}^{Feed-in}) * \tilde{p}_{Feed-in}] \tag{3}$$

Case Study, Implications, and Limitations

To present the applicability of our DSS, we conducted a case study with two household scenarios based on weather and temperature data of Hanover, Germany. Scenario A addressed a two-person household, and scenario B included a four-person household. The most relevant scenario parameters regarding living space, energy consumption, electricity price, and capital expenditures can be found

Table 4: Technical parameters of considered components and units.

Component	**Technical parameters**
Photovoltaic System (PVS)	Area [m^2], Maximum power output [kW p], Efficiency rate η_{PVS} [%] Inclination [°], Alignment of PV modules [°], Shading coefficient [%]
Battery Storage (BS)	Capacity [kW h], Maximum charge rate [kW], Maximum discharge rate [kW], Efficiency rate η_{BS} [%]
Hot Water Storage (WS)	Capacity [kW h], Maximum charge rate [kW], Maximum discharge rate [kW], Efficiency rate η_{HWS} [%]
Heat Pump (HP)	Maximum nominal power [kW], Coefficient of performance [$\frac{P_{out,th.}}{P_{in,el.}}$]
Electrical Vehicle (EV)	Mileage [km/a], Relative consumption [kW h/km]

in [53]. A selected outstanding result for the four-person household is visualized in Figure 10. We have divided each scenario into two cases, as can be derived from Subfigures (4.1) and (4.2). While case (4.1) assumed a feed-in tariff $\tilde{p}_{Feed-in}$), case (4.2) enabled surplus electrical energy to be sold exclusively at the market price $\tilde{p}_{EEX}$. The red dots represented the incremental investment decisions of $2,500$ €. The green, red, and orange curves indicate the cost reduction for investments in the particular component. The dashed and dotted curves depicted the progression of the performance indicators DoA and DSC. The results of our case study demonstrated that, despite the falling feed-in remuneration, PVS investments dominated compared to the battery and hot water storage. However, the comparison between Subfigures (4.1) and (4.2) also showed that investment decisions are sensitive to the feed-in tariff. As an anticipated result, the investments in storage technologies also led to a significant increase in the performance indicators. More self-produced energy was retained in the building energy system.

Both our basic assumptions about incremental investments and our case study were subject to some limitations. Due to technical restrictions, the PVS, BS, and WS components cannot be expanded modularly. For instance, expanding the PVS capacity would also lead to increasing the inverter power. Such technical barriers were not considered in the investment decisions. Measuring economic efficiency by cost reduction represented a significant simplification of reality. Our economic analysis would have required further parameters to create more meaningful implications. Furthermore, our results are location-specific due to weather and economic data and, therefore, cannot be generalized to other locations worldwide.

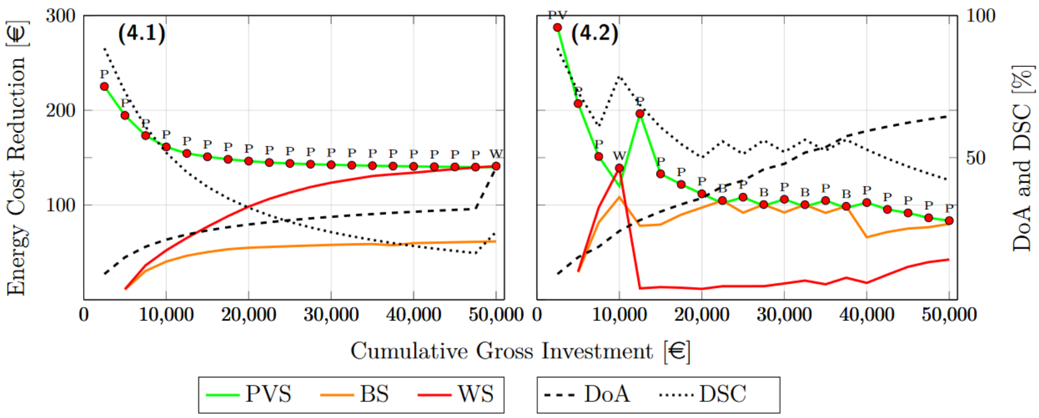


Figure 10: Overview of energy cost reduction for a four-person household.

2.1.2 Retrospective on Contributions, Limitations, and Impact

In retrospect, this article is contextualized concerning Green IS research and the *NESSI* research project. To the latter, this article represents the first publication for this research project and provides the groundwork for both the research design and DSS development. Today's version of *NESSI* continues to be based on a DSR approach whose origins can be found in this article. The fact that the article was published in a Green IS track indicated that the community or Special Interest Group Green (SIGGREEN) perceived this article as contributing to this research field.

2.2 Transformation to Sustainable Building Energy Systems: A Decision Support System

This section summarizes the article *Transformation to Sustainable Building Energy Systems: A Decision Support System* written by Tobias Kraschewski, Tim Brauner, Sarah Eckhoff, and Michael H. Breitner (Appendix A.2). It has been published in the Proceedings of the 41st International Conference on Information Systems (ICIS) in 2020. This article was presented as part of the *Societal Impact of IS* track. It builds on Section 2.1 and expands previous research.

2.2.1 Summary of contents

The 17 Sustainability Development Goals (SDGs) of the United Nations (UN) and the Paris Agreement of 2015 outline directives to mitigate the devastating effects of global climate change. One of the key objectives is to drastically reduce

CO_2 emissions across all sectors, such as energy supply, transport, and building and construction. The latter was responsible for 36% of global final energy use and emitted 39% of all energy- and process-related CO_2 emissions in 2018. Thus, the sustainable transformation of the building energy systems (BESs) represents significant leverage to reduce CO_2 emissions.

Investment decisions are often complex for building owners and stakeholders due to numerous constraints, such as technical complexity for energy technology, volatile energy prices, dynamic regulations, and support schemes. Therefore, decision support is required where stakeholders can inform themselves about their status quo and are provided with transformation paths to a more sustainable energy system. In this context, the core rationale of our DSS approach comes in.

The Green IS community's commitment is to utilize the transformative power of IS to address the challenges of climate change. [4] called in 2010 that '*we need to show leadership in applying the transformative power of IS to create an environmentally sustainable society*'.

We developed a user-centric and problem-oriented DSS called *Nano Energy System Simulator* (*NESSI*) from this. *NESSI* is designed to address building owner decision problems and provide versatile energy system analysis with complexity reduction. Moreover, *NESSI* is designed to answer the following research question:

> *How can a DSS be developed to visualize and simulate the environmental and financial impact of different building energy systems configurations to raise awareness and encourage actions by stakeholders?*

Theoretical Background and Related Research

The theoretical background of DSS development is derived from the Green IS and Energy Informatics research domains. In [4], Green IS was defined as "an integrated and cooperating set of people, processes, software, and information technologies to support individual, organizational, or societal goals." These goals include improving environmental practices such as inefficient resource use, energy consumption, and high emissions. Increasing renewable energy technologies again is a central goal of Energy Informatics [76]. Our DSS artifact addresses these objectives; thus, EI forms the theoretical background. The number of related energy system analysis tools is high, confirmed by review literature of [69–72]. We compared *NESSI* with two established analysis tools. The *HOMER* tool can evaluate the optimal configuration and size of energy components based on optimization. Incorporating technical and economic parameters ultimately minimizes net costs. [70] and [71] emphasized the *HYBRID* tool that provides high prediction accuracy of the performance of energy systems with multiple energy carriers. Due to their complexity and comprehensiveness, both tools are directed to research and experienced users from the industry (engineers, such as power grid planners). *NESSI* addresses experienced and less knowledgeable users through intuitive and simplified usability. In order to take the stakeholder perspective, the technical, economic, and ecological effects of investments in their energy system are evaluated.

Research Design

DSR is a significant research category of DSS development [2]. We use [7]'s three cycles view to demonstrate how we have incorporated relevance, design, and rigor into our development process. We derive the relevance of the problem formulation from the 17 SDGs and the Paris Agreement. Regarding the rigor cycle, we reviewed related energy system analysis tools, followed energy system modeling techniques, and applied validated economic, ecological, and technical parameters. Relevance and rigor cycles guided our design cycle, which resembles a software engineering approach. This is summarized in Figure 11. The undertaken steps of the software engineering process are described in detail in [54]. The criteria of comprehensibility, accessibility, and usability formed the overarching design guidelines.

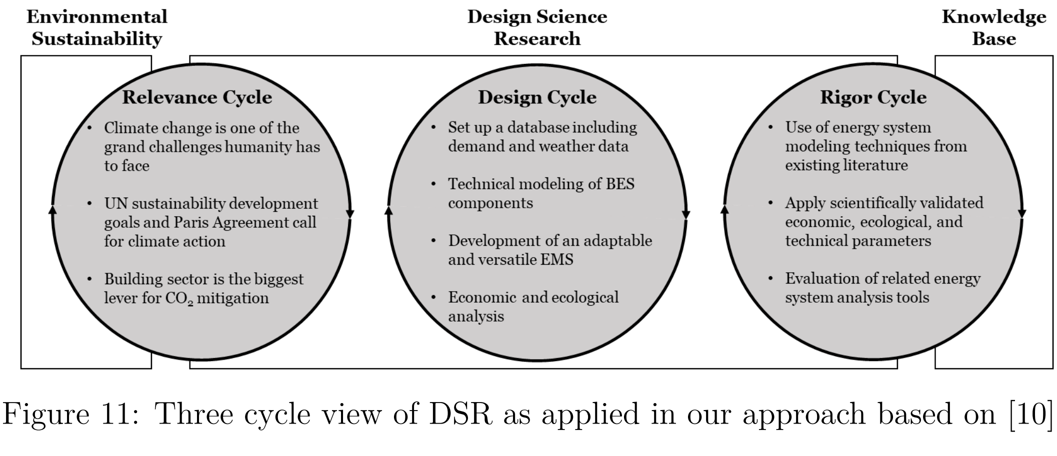


Figure 11: Three cycle view of DSR as applied in our approach based on [10].

Nano Energy System Simulator

NESSI's system architecture is represented in Figure 12. It shows the relationship between the GUI and the data flows underlying it. The entire artifact is built in the MATLAB R2019b numerical computing environment. General, technical, and economic input parameters are required before a calculation can be started in *NESSI*. The load profile generator of [75] is used to create load profiles depending on inputs. A heat load profile is created using outside temperature and building data. Radiation data is used to calculate the solar or thermal yield from the PV or solar thermal systems. Load and yield profiles belong to preprocessing. Depending on the selection of components, the Energy Management System (EMS) is adapted to start an hourly simulation, including one year. In [54], we present *NESSI's* rule-based EMS and explain the basic assumptions used to develop the EMS. Furthermore, we describe the techno-economic analysis and the ecological footprint calculation, which are part of the output parameters of *NESSI*. The investment valuation is based on the net present value (NPV) method according to [77]. The NPV is distributed as annuities throughout the project. Each fossil fuel is assigned an emission factor. Moreover, consumption of electricity from the public grid has also an emission factor. With the help of the consumption of energy sources, the annual emissions can be calculated.

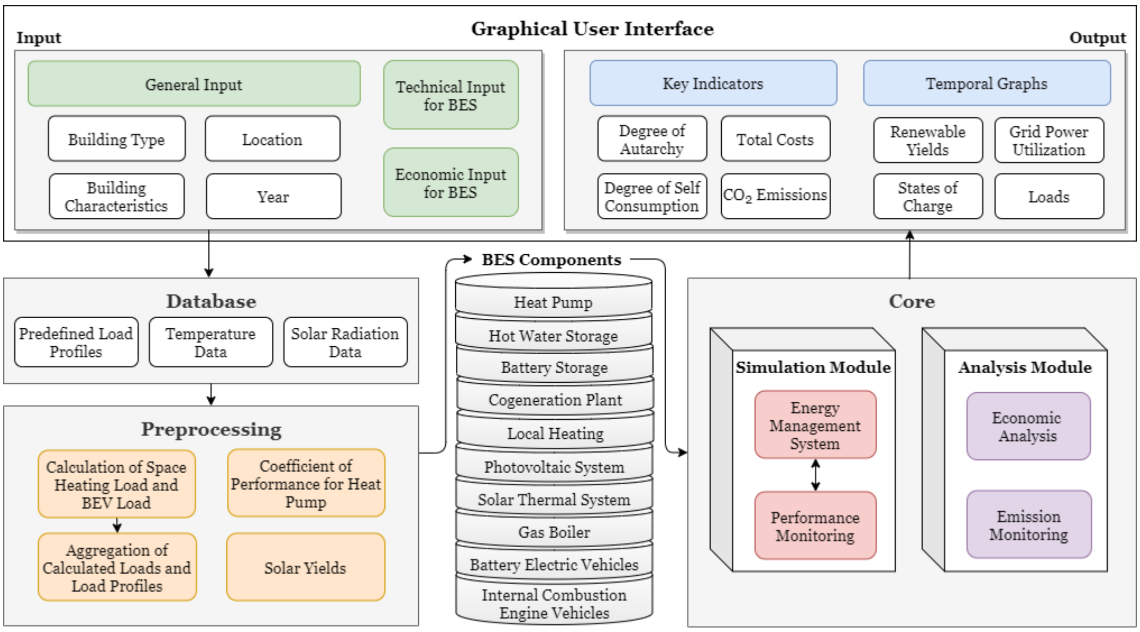


Figure 12: System architecture of *NESSI*.

Computational Study, Discussion, and Recommendations

We presented the applicability and validity of *NESSI* in the context of a computational study. A detached family house and an office building in Hannover, Germany, were defined as scenarios. *NESSI* was used to calculate the economic and environmental performance of different energy system configurations for both scenarios. Details on the underlying assumptions and further analysis of the computational study can be found in [54]. As expected, the computational study results are strongly dependent on the input parameters. Detailed analyses and conclusions about the scenarios were drawn, but the results cannot be generalized. The scenario results have confirmed that increasing environmental performance is always accompanied by high overall costs and, thus, limited feasibility. Moreover, the effect of a CO_2 tax is discussed based on two selected scenarios.

Limitations and Outlook

Computational study-related limitations are explained in [54]. The most critical DSS-related limitations are briefly summarized below. Since *NESSI* integrates a wide range of energy components, some technical processes are modeled in a simplified way. Short-term effects in the minute or second range cannot be displayed with *NESSI*. More in-depth technical simulations increase the calculation times and thus limit the applicability. Furthermore, *NESSI* is grounded on a rule-based EMS simulation approach. It is contrasted with optimization approaches that ensure more efficient energy use or perfect sizing of energy system components. However, optimization approaches are based on the assumption of perfect foresight, which weakens real-world applicability. Finally, economic analysis using the NPV method is a common practice, but there are drawbacks in considering uncertainties such as changing capital and risks. These limitations indicated where *NESSI* could be complemented or improved in future research.

2.2.2 Retrospective on Contributions, Limitations and Impact

The publication of this research article at ICIS 2020 represented an important milestone for DSR Project *NESSI*. It was the first time the DSS was presented to a broader audience in the IS domain. After three years, the scientific impact of the article can be classified as low. No external citations have been recorded at this time. However, the article has led to the establishment of this DSS in the Green IS area and intensified further research work. The most significant technical limitation of the *NESSI* is using the licensed programming language MATLAB. Regarding methodological limitations, the DSS has not been evaluated sufficiently with stakeholders from science and industry.

2.3 Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Energy System Simulator NESSI

This research article *Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Energy System Simulator NESSI* ([55]) was written by Sarah Eckhoff, Maria C. G. Hart, Tim Brauner, Tobias Kraschewski, Maximilian Heumann, and Michael H. Breitner and has been accepted by the journal *Building and Environment* (Appendix A.9). Currently, it has a two-year IF of 7.09 [47]. This research article represents *NESSI's* most comprehensive and detailed summary.

2.3.1 Summary of Contents

The calls of [4] and [5] for solution-oriented IS research to address climate change represent the motivational background of *NESSI*. Other IS scholars like [3] have emphasized the importance of carbon emission reduction through DSSs. Lack of out-of-the-box functionality and practitioner involvement have been criticized concerning academic energy models by various scholars [11, 12, 78]. These criticisms are addressed in this article. *NESSI* is presented transparently in seven steps using [9]'s DSR publication scheme. Within this publication scheme, we used the DSR methodology of [8].

Literature Review, Objectives, and Requirement Definition

The body of academic literature regarding energy system analysis-related models and software tools has grown extensively in the last two decades. Multiple review articles (e.g., [11, 12, 71, 79–81]) presented a high amount of literature in the field of energy models and software tools. Despite countless energy models and software tools, high impact and usability in the academic field can only be assigned to a few models. We tested well-known models and tools like *HOMER* [82], *RETScreen* [83], *iHoga* [84], and *Hybrid2* [85], and compared them to the DSR project *NESSI*. Furthermore, we reviewed more than 80 listed models of the platform *openmod* [86]. Some sub-models like *pvlib* [87] and *LoadProfileGenerator* [75] are implemented in

NESSI to calculate yield profiles of photovoltaic systems and generate household load profiles. Although we reviewed numerous energy models and software tools, none sufficiently met all criteria (e.g., purpose, geographical and sectoral coverage, time horizon, temporal resolution, out-of-the-box functionality, open-accessibility, user-friendliness, comprehensibility).

To ensure rigorous DSS development, we conceptualize stakeholder-, model-, and system-oriented requirements to *NESSI* according to [88]. We defined citizens that own/manage residential or commercial buildings, energy consultants, housing associations, and municipal administration as *NESSI's* stakeholders. The in-depth requirements elaboration can be found in [55].

Artifact Description

The artifact description encompasses the software architecture, simulation procedure, and demonstration by presenting the user flow of *NESSI* with two scenarios. Figure 13 describes the general software architecture of *NESSI* using a *Docker* server that encompasses nginx, web application, and database containers. Moreover, there is an interface with a second server that provides NASA Merra2 weather data.

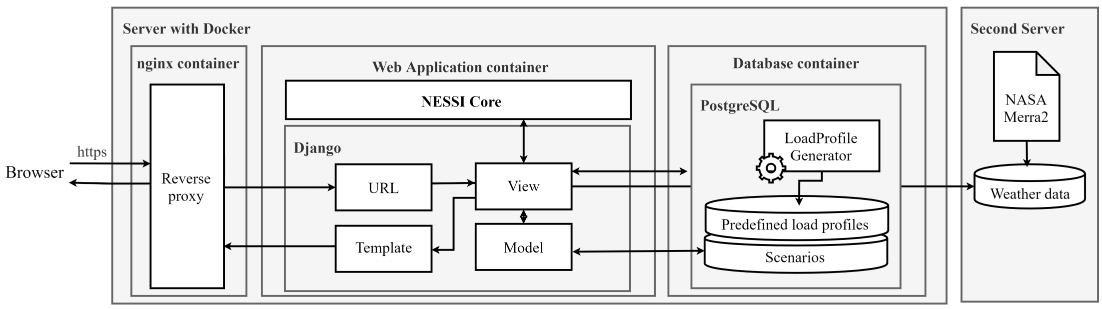


Figure 13: Final software architecture of *NESSI*.

The software is mainly based on Python 3.10 to ensure comprehensibility in the scientific community. Regarding technical specifications, *NESSI* has been implemented using full stack state-of-the-art web framework *Django* 3.1.6. As illustrated in Figure 13, the entire software architecture is encompassed by a Docker container, allowing *NESSI* to be conveniently deployed on other devices and systems.

NESSI can simulate individual buildings and neighborhoods. The two cases are subject to a similar simulation, but the neighborhood simulation model includes several building objects. The general simulation procedure is four-staged. First, the load profile arrays, such as electrical load, hot water demand, space heating demand, and cooling demand, are generated based on the user inputs. In the second step, a reference scenario is created that includes all existing components and thus provides a comparative benchmark for subsequent economic and ecological analyses. Third, all user inputs are pre-processed and fed into the *NESSI* kernel, the rule-based simulation model. In the last step, the calculated scenario with the new components is compared with the reference scenario, and an investment evaluation is made. The user can evaluate the scenarios based on various key performance indicators (KPIs). By default, scenarios are calculated for an annual period. However, multi-year simulations can be carried out in which parameters such as electricity prices or energy consumption can be changed over time. Those scenarios, however, require a longer calculation time than single-year simulations. A thirteen-component energy management system (EMS) constitutes the kernel of *NESSI*. It is a rule-based EMS, which covers all energy demands with the given components in hourly time resolution. This is indicated in the later analysis in case of a coverage deficiency. All EMS rules and an energy flow diagram are presented in [55]. To transparently exemplify the usage of *NESSI*, a use case of a single-family homeowner is demonstrated. The associated user flow is shown in Figure 14. It also highlights individual input steps and corresponding screenshots of the web tool. The use case addresses the decision to invest in a heat pump in the presence of a PV system with battery storage. Under the specified scenario parameters, the investment in a heat pump can achieve cost savings in the amount of 10,000 €. An amortization period of ten years can be achieved. Further economic and environmental KPIs regarding the use case can be found in [55].

Evaluation

As part of the DSR research process (e.g., [8, 9]), we executed an evaluation stage including *NESSI's* online usage, stakeholder interviews, and feedback from public events. A total of twelve expert interviews were conducted with stakeholders from industry and academia to assess *NESSI* and derive improvement points. Stakeholder-, model-, and system-oriented criteria were categorized as per [88]. In the following, selected aspects that were discussed during the expert interviews are outlined. Some experts welcomed the division into default and expert settings and perceived significant added value from *NESSI* for energy consultants in assisting homeowners in the decision-making process. Probably the most impact-

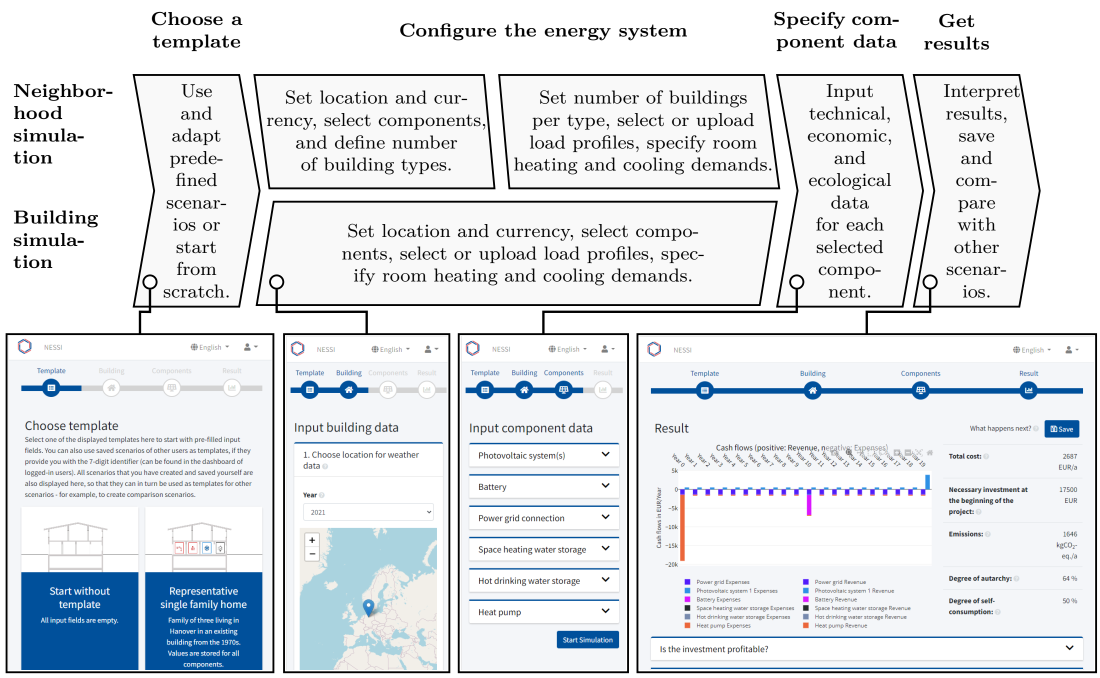


Figure 14: User flow of neighborhood and building simulation with exemplary screenshots.

ful improvement point was the separation of the thermal infrastructure into hot water and space heating circuits. This technical requirement was implemented and significantly impacted the rule-based EMS. Although the scenario templates have been made more representative and the development of *NESSI* has generally taken a complexity-reducing approach, a few experts have expressed concern that the DSS may be too complex for inexperienced users. We have taken these concerns thoughtfully and, for example, created help texts for more complex input parameters.

Table 5: Overview of evaluation interviews experts.

#	Job description	Domain of operation	Field of expertise
1	Sustainability lead	Consulting and service	Development of energy concepts for quarters
2	Project engineer	Climate protection agency	Neighborhood energy concepts, municipal heating planning
3	Program director	Climate protection agency	Climate protection education, renewable energies in buildings
4	Scientist	High voltage technology and power systems	Energy management and energy economics
5	Scientist	Supply engineering	Supply engineering and facility management
6	Electrical engineer	Climate protection agency	Renewable energies and energy systems
7	Civil engineer	Climate protection agency	Energy optimization of buildings
8	Branch manager	Software and service	Geo-informatics and facility management for public administrations
9	Project manager	Software and service	Heat demand analysis and heat planning
10	Financial manager	Distribution grid operator	Financial analysis
11	Financial manager	Distribution grid operator	Financial analysis
12	Quality manager	Transmission grid operator	Internal knowledge management

Discussion and Conclusions

In [55], other use cases (e.g., subsidy evaluation, technology comparisons, electric-mobility) of *NESSI* are presented, and controversial aspects from the expert interviews are discussed. It includes the dilemma of diverse stakeholder-related requirements, some of which cannot be met simultaneously. Some experts requested technical details (e.g., separation of hot water and space heating circuits), while others raised concerns that the DSS may be too complex for inexperienced users. This conflicting issue is discussed, and its influence on the development of *NESSI* is outlined. Furthermore, *NESSI's* simulation kernel is contrasted with an optimization approach. The core idea of the DSS is to provide the user with understandable information to transfer into tangible actions. This goal is supported by [89], who confirmed that simulation tools are better suited for long-term decisions than optimization models. In addition, optimization models are often associated with higher computation times and thus limit their applicability.

2.3.2 Retrospective on Contributions, Limitations, and Impact

This research article showcases the most mature version of *NESSI* and represents a milestone for nearly five years of development. In particular, compared to [53, 54] the migration of a once MATLAB-based to a Python-based DSS represents the most significant change. This enabled the open-access nature of *NESSI* and, furthermore, easier development into a web-based tool. Another distinct feature of this research article is the extensive evaluation through public engagements, increased web usage, and twelve expert interviews. Within the framework of a DSR project according to [8], the evaluation of the artifact represents a decisive step. This was only substantiated to a limited extent in [53] and [54] and hereby an evaluation cycle with all stakeholders was carried out.

A difficult limitation to solve is the large stakeholder group and the resulting heterogeneous requirements for the DSS. A one-fits-all version of *NESSI* is virtually impossible to implement due to the partially conflicting requirements of the stakeholders. How to address this problem and what follow-up questions arise will be discussed in Section 5. Fortunately, this research article was recently accepted by *Building and Environment*. With this, the author team has reached the next major milestone and positioned the most mature version of *NESSI* in a journal. Due to the article's recent acceptance, no conclusions can yet be made about its potential impact on the scientific community. Nevertheless, the author team hopes that this publication will increase the visibility and relevance of *NESSI*.

2.4 Classification of Real-World Microgrids Based on a Morphological Analysis

This section summarizes the completed research article *Classification of Real-World Microgrids Based on a Morphological Analysis* written by Jana Gerlach, Sarah Eckhoff, Oliver Werth, Tobias Kraschewski, Tim Brauner, and Michael H. Breitner (Appendix A.3) [58]. The article has been virtually presented in *Green IS and Sustainability* track at Americas Conference on Information Systems (AMCIS) in 2021.

2.4.1 Summary of contents

The growing prevalence of distributed energy resources (DERs) represents a paradigm shift from centralized, emissions-intensive, and low-end-use efficiency energy systems. However, it is a challenge to operate a high number of DERs with Information and Communication Technology (ICT) securely and efficiently in a network. In the context of increasing decentralization of DERs, microgrids (MGs) have emerged as a promising solution addressing this challenge. According to the European Commission, MGs are '*low-voltage distribution systems with distributed energy sources, devices and controllable loads operated connected to the main power network or islanded, in controlled, operated way*' [90]. The planning, design, and implementation of MGs require the involvement of numerous stakeholders, including distribution network operators (DNOs), ICT and energy technology manufacturers, and service providers.

Although a few research papers on MG design exist (e.g., [13, 14]), the literature regarding the classification of MGs and successfully implemented MG projects is limited. Based on a literature search and morphological analysis, we investigated the current research on MG design options and extracted a morphological box to classify real-world MGs. Thereby, we addressed the following research questions:

> *RQ1: Which MG design options can be extracted from literature using a morphological analysis?*
> *RQ2: How can real-world MGs be classified using the morphological box and which implications and recommendations for future research and practice can be derived?*

Research Design and Methodology

Based on methodologies of [15–17], we conducted a systematic and keyword-based literature search to identify MG design literature. It resulted in the extraction of 30 articles. After performing backward, forward, author, and *Google Scholar* similarity searches, we consolidated 36 articles. Our morphological analysis was based on [18]. Morphological analysis can be used to identify problem dimensions and examine their relationships, thus, reducing complexity [91]. [92] used morphological analysis as an underlying methodology to derive solutions for an interdisciplinary and multi-dimensional research topic. To apply our morphological box, we searched for real-worl MGs online. In total, we identified 47 MGs, but we discarded 17 of them due to a lack of documentation. More in-depth research design and methodology information can be found in [58].

Morphological Analysis

Based on the 36 collected articles, in particular, [13, 14, 93–95], we derived the five layers *Governance, Business, Intelligence, Communication, and Physical* for our morphological box. Each layer is divided into dimensions D_i defined by different characteristics $C_{i,j}$. Table 6 presents the entire morphological box and includes five layers, 18 dimensions, 60 characteristics, and utilized references. An in-depth description of the five layers, including an explanation of which characteristics were derived from which reference, can be found in [58].

Classification of Real-World Microgrids and Discussion

Based on our literature search of real-world MGs, we utilized the morphological box to classify 30 MG projects. The 30 MG projects are divided into four campus-related, seven commercial- and industrial-related, eight community- and utility-related, three military, and eight remote MGs. The MG projects are spatially divided among the following continents: twelve in North America, three in South America, four in Asia, six in Europe, three in Africa, one in Australia, and one in Antarctica. Each MG was assigned to a maximum of one characteristic in one dimension to adhere to the rationale of the morphological box. The classification and characterization of the 30 MGs projects is presented in Table 2 in [58].

Table 6: Morphological box for microgrid design options.

Layer	Dimensions D_i	Characteristics $C_{i,j}$		References
Governance	D_1 Objectives	$C_{1,1}$ Economic $C_{1,3}$ Technological $C_{1,5}$ Multi-objective	$C_{1,2}$ Social $C_{1,4}$ Environmental	[96]
	D_2 MG ownership	$C_{2,1}$ Distribution network operator/ utility $C_{2,3}$ Independent	$C_{2,2}$ Customer or consortium of customers	[97]
	D_3 State support	$C_{3,1}$ None	$C_{3,1}$ Yes	[14]
Business	D_4 Internal business model	$C_{4,1}$ None $C_{4,3}$ Local energy market $C_{4,5}$ Multiple	$C_{4,2}$ Demand response $C_{4,2}$ Outage resilience	[95, 98, 99]
	D_5 External business model	$C_{5,1}$ None $C_{5,3}$ Ancillary service	$C_{5,2}$ Electricity export $C_{5,4}$ Multiple	
Intelligence	D_6 EMS functions	$C_{6,1}$ None $C_{6,3}$ Scheduling /controlling	$C_{6,2}$ Monitoring $C_{6,4}$ Optimizing	[95, 100]
	D_7 EMS architecture	$C_{7,1}$ None $C_{7,3}$ Dec. in MG	$C_{7,2}$ Building $C_{7,4}$ Central. in MG	[101, 102]
	D_8 Forecast	$C_{8,1}$ None	$C_{8,2}$ Yes	[103]
Communication	D_9 Metering	$C_{9,1}$ None $C_{9,3}$ Continuous	$C_{9,2}$ Cumulative	[92]
	D_{10} Sensors and actuators	$C_{10,1}$ None $C_{10,3}$ Advanced	$C_{10,1}$ Basic	[14]
	D_{11} Communication network	$C_{11,1}$ None $C_{11,3}$ To other parties outside the MG	$C_{11,2}$ Within the MG $C_{11,4}$ Both	[14]
Physical	D_{12} MG connection	$C_{12,1}$ Physical $C_{12,3}$ Both	$C_{12,2}$ Virtual	[13]
	D_{13} Connectivity to utility grid	$C_{13,1}$ Islanded $C_{13,3}$ Dual-mode	$C_{13,2}$ Grid connected	[95]
	D_{14} Power flow	$C_{14,1}$ None $C_{14,3}$ Bidirectional	$C_{14,2}$ Unidirectional	[14]
	D_{15} DERs	$C_{15,1}$ 100% fossil $C_{15,3}$ 100% renewable	$C_{15,2}$ Mixed	[104]
	D_{16} Power supply	$C_{16,1}$ External $C_{16,3}$ Local generation	$C_{16,2}$ Partly external import and dec. generation	[105]
	D_{17} Electrical storage	$C_{17,1}$ None $C_{17,3}$ Mixed	$C_{17,2}$ Building energy storage $C_{17,4}$ Community energy storage	[93]
	D_{18} Sector coupling	$C_{18,1}$ None	$C_{18,2}$ Yes	[105]

2.4.2 Retrospective on Contributions, Limitations, and Impact

With regard to citations in academia, only a low impact can be attributed to this article. Nevertheless, it should be emphasized that this article has established the start of further research on the classification of MGs. During a paper development workshop at AMCIS 2021, this article attracted attention and the authors were invited to make another more mature submission to a higher-tier journal. Unfortunately, this submission has not yet resulted in success, however, experienced scholars have attributed high relevance and potential to this topic.

2.5 Disentangle the Price Dispersion of Residential Solar Photovoltaic Systems: Evidence from Germany

This section summarizes the article *Disentangle the Price Dispersion of Residential Solar Photovoltaic Systems: Evidence from Germany* (Appendix A.8). The article was written by the collaboration of Tobias Kraschewski, Tim Brauner, Maximilian Heumann, and Michael H. Breitner. We submitted the article to the peer-reviewed journal *Energy Economics* from *Elsevier* on 14.09.2022. This article was accepted after one revision and one replication audit and will be published soon. According to *Scimago's* journal rankings, *Energy Economics* ranks as a *Q1* journal in Economics and Econometrics, and Energy [46]. In particular, in the subject area Energy, *Energy Economics* is among the best ten outlets and has a 2-Year IF of 9.25 [45].

2.5.1 Summary of contents

The following concisely elaborates on our motivation, research question, theoretical background, and methodology and highlights our findings. Germany has the largest installed capacity of solar photovoltaic (PV) systems in Europe with 58.4 GW [106]. Rooftop PV systems are highly relevant in this context, as they are not in spatial competition with other energy technologies and represent the most socially accepted renewable energy technology [107]. Despite high social acceptance, the economic viability of PV systems strongly influences the decision of homeowners. The system costs, and the expected energy yield are decisive when evaluating the economic viability of PV systems. Here, our research proposal begins. Although Germany has a large and mature roof PV market compared to other European countries, it is challenging for many homeowners to evaluate whether they received a fair quote. There needs to be more price transparency in the market. Furthermore, from the perspective of policymakers, it is relevant to understand which factors must be addressed to establish reasonable PV system prices and thus amplify installations. Based on the market price transparency problem, we address the following research questions:

> *RQ1: Which factors affect rooftop solar photovoltaic system prices in Germany?*
> *RQ2: What factors are particularly price-determining for system quantiles?*

Related studies on the decomposition of PV system prices have been carried out mainly in the US. [19] provides results on the deconstruction of solar PV pricing. [20] and [21] have investigated factors that affect low-priced PV systems, in particular, and associated characteristics of those systems. Moreover, [22] and [23] has emphasized the importance of price transparency in residential PV markets and effects of PV installer market concentration on system prices.

Data

We initially collected 21,828 quotes from the domain `www.photovoltaikforum.com`. The quote data range over the period from January 2011 to December 2022. The quote data includes the following features: total PV system price, postal zip code, module and inverter characteristics, and additional information about the system. The reported system costs comprise hardware costs for modules, inverter, wiring, support structure, and meters. Additionally, system costs encompass soft costs for labor, marketing, permitting, overhead expenses, and installer profit. Besides the costs, details are provided on system characteristics such as capacity, battery storage, or full installation service. We added more features to create a comprehensive and in-depth dataset and conducted several data-cleaning steps. We have cross-referenced the data on modules and inverters with the two databases `https://www.photovoltaikforum.com/mdb/` and `https://www.secondsol.com/en/datasheet/inverter/`. It enabled us to add module efficiencies and inverter power ratings to the quote data. The module efficiency serves as a quality indicator. We grouped modules by year, normalized the modules' efficiencies, and thus added the module rating parameter. Furthermore, all PV systems with *Solaredge* inverters were assigned the DC Optimizer attribute.
Based on the location information of the PV quotes, we complemented the dataset

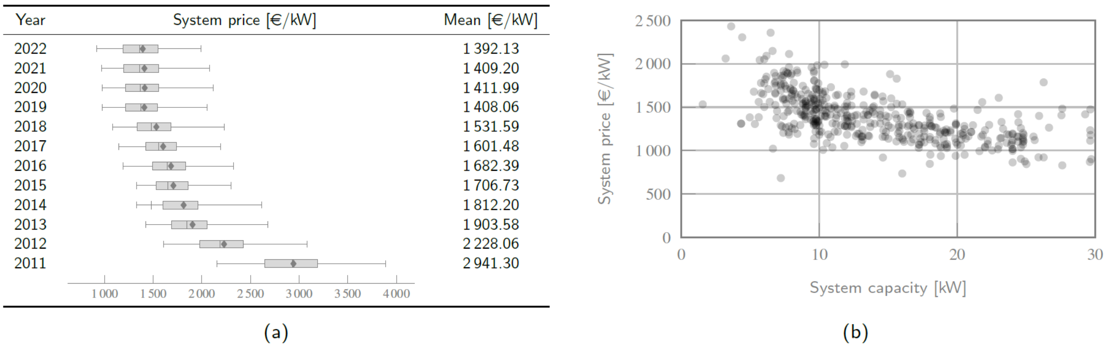


Figure 15: PV system prices from 2011 to 2022 (a) and PV system prices as a function of system capacity for 2022 (b). PV systems with battery storage or self-installations were left out.

with socio-economic and demographic variables. Using multiple sources, we added average income, population density, and wages on either two-digit postal code or federal state level. We cleaned the original dataset of 21,828 quotes, which left 19,561 quotes to be used for further economic analyses. The data cleaning process excluded quotes with missing location information, missing hardware data, incomplete zip codes, or a location outside of Germany. Other data sources that were used to complement the dataset are explained in [61].

The final dataset is analyzed descriptively in Figure 15 using annual boxplots of system prices and a capacity-dependent scatterplot of system prices. Figure 15 (a) shows that PV system prices have strongly reduced between 2011 and 2013. This trend was due to a sharp reduction in the cost of PV modules [108]. However, PV system prices have stagnated since 2020, mainly due to the rising commodity price of polysilicon and global supply chain issues [109]. Both graphs demonstrate high variability in system prices despite the same capacity. Concerning the scatterplot in Figure 15 (b) demonstrating system prices from 2022, the mean value is at 1392.1 €/kW and the standard deviation is at 284.6 €/kW. The standard deviation again highlights the high price heterogeneity. Further descriptive information on the data set can be found in [61].

Methodology and Model Specification

Methodologically, we applied a hedonic pricing model according to [110] and a quantile regression model according to [111]. We can use hedonic price modeling to estimate the implicit price of the system characteristics and location- and installation-related variables on the reported quote price. This approach is based on ordinary least squares (OLS) regression. Hedonic price models are adequate for measuring the influence of factors on price dispersion, which is underlined by several studies [112–115]. Transferred to our study, we regress the PV system price (Y) on several hedonic covariates X, which comprise system characteristics (C), installation scopes (S), and location-related factors (L). Further, we add location fixed effects at two-digit postal zip code level θ_j. Equation (4) defines our general hedonic PV quote price model:

$$Y_{ijt} = \alpha + \beta_1 C_{it} + \beta_2 S_i + \beta_3 L_{jt} + \theta_j + \epsilon_{ijt} \tag{4}$$

where Y is the PV system quote price in natural log form, α is the intercept term, β is the variables' associated coefficients, and ϵ is the normally distributed error term. The subscript i denotes the quoted PV system, t denotes the quote's year, and j denotes the respective location.

In contrast to OLS regressions, quantile regression, which was first introduced by [111], is based on the minimization of weighted absolute deviations to estimate conditional quantile functions. In this research article, quantile regression is applied to investigate the effects of the independent variables on different PV system price segments. Nine quantiles ($\tau = 0.1, ..., 0.9$) are considered to draw conclusions about each quantile τ^{th}. As in OLS regression, a linear relationship between Y and X was assumed. The probability density function is therefore $F_Y(y) = Prob(Y) \leq y$. This results in the quantile regression in Equation (5):

$$Q_Y(\tau) = F_Y^{-1}(\tau) = \inf\{y : F_Y(y) \geq \tau\} \tag{5}$$

The distribution is split in proportions above $(1 - \tau)$ and below τ. The respective quantile regression estimators $\hat{\beta}_\tau$ can be found through:

$$Q\left(\hat{\beta}_\tau\right) = \sum_{y_{ij} > \hat{\beta}_\tau X_{ij}} \tau \left|y_{ij} - \hat{\beta}_\tau X_{ij}\right| + \sum_{y_{ij} < \hat{\beta}_\tau X_{ij}} (1 - \tau) \left|y_{ij} - \hat{\beta}_\tau X_{ij}\right| \tag{6}$$

Additional details on model specifications of the hedonic price model and quantile regression can be found in [61]. In addition, it also summarizes the key statistics on the dependent variable system price and the continuous and categorical independent variables.

Table 7: Regression results.

	OLS		Quantile regression				
	REF	***LOC-FIX***	***Q10***	***Q30***	***Q50***	***Q70***	***Q90***
Constant	7.0668***	7.1029***	6.8296***	6.9417***	7.0401***	7.1509***	7.3134***
System characteristics							
System capacity	-0.4210***	-0.4049***	-0.3915***	-0.3926***	-0.3993***	-0.4150***	-0.4189***
Module quality	0.0280***	0.0273***	0.0258***	0.0166***	0.0199***	0.0241***	0.0578***
Module price index	0.5010***	0.5163***	0.5350***	0.5679***	0.5698***	0.5193***	0.4054***
Inverter price index	0.2557***	0.2474***	0.2278***	0.2123***	0.2086***	0.2431***	0.3272***
DC optimization	0.0728***	0.0685***	0.0648***	0.0703***	0.0768***	0.0835***	0.0835***
Battery	0.5102***	0.5143***	0.4274***	0.4927***	0.5135***	0.5391***	0.5854***
Installation scope							
Full installation	0.2009***	0.2005***	0.2519***	0.2203***	0.1991***	0.1788***	0.1514***
AC installation	0.0174***	0.0183***	0.0230***	0.0137**	0.0169**	0.0146*	0.0059
Scaffold	0.0264***	0.0289***	0.0246***	0.0254***	0.0257***	0.0250***	0.0206***
Elevation	0.0238***	0.0234***	0.0123**	0.0185***	0.0237***	0.0226***	0.0263***
Location							
Radiation	0.0624***		0.0593***	0.0578***	0.0609***	0.0683***	0.0658***
Installations	0.0656***		0.0406**	0.0633***	0.0700***	0.0659***	0.0673**
Wages	0.0443***		0.0511***	0.0580***	0.0514***	0.0364**	0.0329*
Installer density	-0.1244***		-0.0960***	-0.1014***	-0.1183***	-0.1289***	-0.1514***
Income	0.0029		-0.0222	0.0176	0.0148	0.0268	0.0276
Location fixed effects	×	✓	×	×	×	×	×
Adjusted R^2	0.767	0.772					
Pseudo R^2			0.5421	0.5487	0.5493	0.5374	0.4706
No. observations	19,561	19,561	19,561	19,561	19,561	19,561	19,561

$^{*}\ p < 0.05$ $^{**}\ p < 0.01$ $^{***}\ p < 0.001$

Results and Discussion

The OLS and quantile regression results are summarized in Table 7. The OLS scenario *REF* represents the baseline. This is compared with the *LOC-FIX* scenario, which includes local fixed effects. Both scenarios show similar results, which underlines the results' robustness.

Two-digit zip code areas are used as categorical variables to investigate local fixed effects. Based on the 96 zip code areas in Germany, significant regional price dispersion of PV systems was shown. System prices can vary by up to 20% depending on the area. An isolated consideration of the factors showed that the spatial price differences could not be explained straightforwardly. Instead, a differentiated assessment of all 16 factors is required to explain the unsystematic price dispersion.

Furthermore, regressions of five price quantiles were performed. It enables more profound insights into the extent to which the 16 factors influence individual PV price segments.
Both the OLS *REF* and quantile regression estimates and their associated confidence intervals are summarized in Figure 16. The effects of some selected factors on the price quantiles are explained in the following. The *full installation* factor has one of the largest effect sizes. In terms of price quantiles, it can be observed that low-priced PV systems experience a more significant price increase compared to high-priced systems. On the one hand, this effect can be explained by the more efficient installation of high-priced systems. On the other hand, the relative cost of full installation service is higher for a low-cost system. Therefore, German homeowners benefit more from self-installation when they purchase a low-priced PV system, which s contrary to [21]'s results in the U.S. market.
Due to scaling effects, the system capacity factor has a price-reducing influence. PV systems with a greater capacity decrease in relative price per unit of output. However, the quantile regressions reveal that the price reduction is more significant for high-priced systems than medium- to low-priced ones. Furthermore, the OLS regression shows that installer density can have a reducing influence of up to 12.44%. This result is consistent with research conducted by [21] in the U.S. market. In addition, the quantile regression reveals that high-priced systems experience a higher price reduction than other systems. The *number of installations* factor indicates that higher demand for PV systems has a price-increasing effect of up to 6.56%. This result confirms that demand is an essential driver in forming residential PV system prices. All other factors are explained and discussed more in [61].

2.5.2 Retrospective on Contributions, Limitations and Impact

This article received final acceptance in March 2023 and will appear in the journal *Energy Economics* [45]. Since the article has only recently been accepted and is in the publication process, no conclusions can yet be drawn about the contributions to the scientific and practical discourse. As *Energy Economics* is one of the leading journals in this domain, the authors hope to substantially impact the community and deliver exciting results for the German PV market. Homeowners and other market players can use the results to make more informed investment decisions. Furthermore, policymakers can use the findings better to understand the German

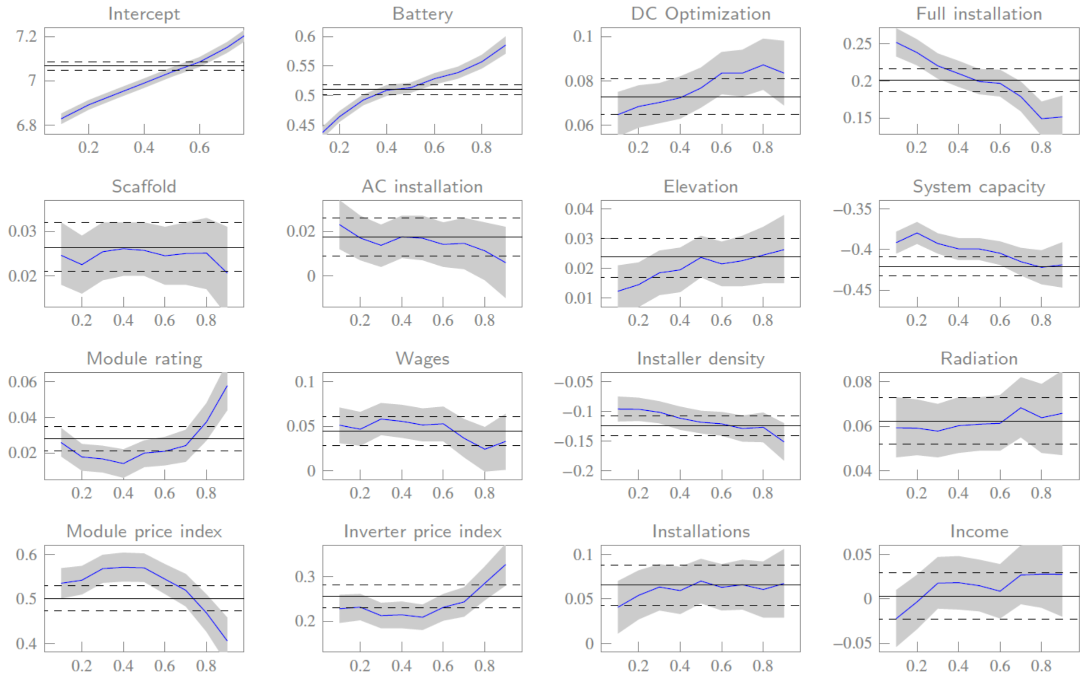


Figure 16: OLS (REF) estimates (continuous horizontal line) with respective CIs as dashed lines, quantile regression estimates (blue line), with respective 95 % CIs as shaded gray area.

PV market on the one hand and to take appropriate regulations or measures to address spatial price dispersion on the other hand.

3 Shared Micromobility Research

Research on shared urban micromobility represents the second pillar of this dissertation. In general, micromobility encompasses shared-use fleets of fully or partially electrically powered vehicles such as electric scooters (e-scooters) and electric mopeds (e-mopeds), and bicycles (bikes) [116, 117]. It represented a relatively new transportation concept in several American cities in 2017. The *National Association of City Transportation Officials* documented 136 million shared station-based and dockless micromobility trips in the U.S. in 2019, and more than 60% of those trips were made on e-scooters [118]. Concerning micromobility use in Europe, [119] used mobility data from 30 cities in 2021 to demonstrate that e-scooter sharing has also become prominent in Europe. This rapid dissemination and increasing relevance of shared micromobility concepts have resulted in many academic studies on its use in space and time. Due to the initial emergence of shared e-scooters and high data availability, studies on usage patterns have been published, especially for American cities (e.g., [120–126]).

In the following three subsections, two published articles and one article under review are presented. Sections 3.1 and 3.2 cover studies on the temporal and spatial use of micromobility in Berlin, Germany. The third article in 3.3 analyzes safety aspects and risk factors in using shared e-scooters.

3.1 A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage

This section summarizes the article *A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage* (Appendix A.4) which was published in the peer-reviewed journal *Sustainability* in November 2021 [59]. According to *Scimago's* journal rankings, *Sustainability* is a *Q1* journal in the subject area of Geography, Planning, and Development [38]. Furthermore, it received a *C* ranking in *VHB JQ3* in sustainability management. According to *Sustainability's* metrics, it has a five-year IF of 4.09 [37].

3.1.1 Summary of contents

Despite advantages such as alternatives for first- and last-mile problems in urban transport, the rapid dissemination of shared e-scooters posed significant challenges to cities. As mentioned at the beginning of Section 3, the first operators started to deploy their shared free-floating e-scooter fleets in US cities in 2017. The first studies (e.g., [121]) on the temporal and spatial use of e-scooters were published in 2019. Established researchers like [123] and [126] called for comprehensive and in-depth analyses of the spatiotemporal use of micromobility concepts. For urban transportation planning, it is essential to understand the use of such shared concepts in space and time to measure the effects on urban transportation and make strategic adjustments. We investigated the spatiotemporal use of e-scooters in Berlin using location data from May 2019 to January 2020. Thereby, we addressed the following research questions:

RQ1: How are shared e-scooters used in space and time in Berlin?
RQ2: How can cluster and land use type analyses contribute to an improved understanding of shared e-scooter usage?

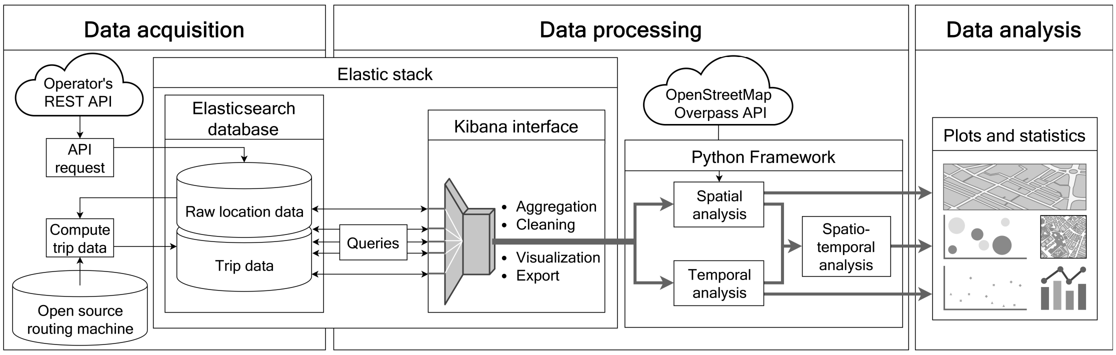


Figure 17: Overview of data acquisition, data processing and data analysis as a data pipeline.

Our complete data pipeline, from data acquisition and processing to spatiotemporal analyses, is presented in Figure 17. We used the application programming interface (API) of the micromobility operator *Tier Mobility* to query the location data of e-scooters. The API queries initially contained raw location data, e-scooter IDs, operating zone, e-scooter manufacturer, and battery state of charge (SOC). We have assigned a timestamp to each query. When e-scooters are moved, their ID is no longer found in an API query. We could identify when e-scooters were being ridden by querying every five minutes. We generated trip data from the locations using an open-source routing machine. We also tracked the changes over time of all other parameters (e.g., battery SOC). Based on related literature (e.g., [121, 124, 127]) and our considerations, we cleaned and categorized the trip data. As summarized by Figure 19, we cleaned the raw trip data using the detour factor (DF) and network-distance (d_N) applying *Open Source Routing Machine* (OSRM). OSRM calculates trip distance based on the shortest bicycle route between the origin and destination. Then, using travel time (Δ_t), energy consumption (E), change in battery SOC (Δ_SOC), average velocity (v), and haversine- (d_H) and network-distance, we developed filtering criteria to establish four distinct ride categories. We have classified trips into user (one-way and round trips) and operator trips (charging and reallocation). Based on $1,250,975$ raw trips, we conducted temporal, then spatiotemporal, velocity, cluster, and point of interest (POI) analyses.

Temporal Analyses

We investigated the temporal usage patterns of the four trip categories for weekdays and weekends visualized in Figure 20. In addition to the network distance d_N, we determined the distance traveled derived from battery SOC change Δ_SOC

and average energy consumption E_{avg} in Subfigures 20 (a) and (b). For one-way trips in Subfigure 20 (a), the network distance d_N and the distance determined by battery change are similar. In contrast, round trips show that the distance derived by energy consumption deviates significantly from d_N.

Regarding one-way trips, we found a specific commuter activity on weekdays from 7 a.m. to 9 a.m. Most one-way trips, however, are made on weekends between noon and 4 p.m. Here, leisure activity can be identified. Also, at night on weekends, especially between midnight to 2 a.m., there is a slight increase in trip volume, which the nightlife and limited public transport can explain. The round trips have a similar temporal daily pattern as one-way trips but with a significantly lower trip volume. Moreover, we have not identified any commuter activity regarding round trips.

Charging trips show high activity from 8 p.m. to midnight. In addition, there is a peak around 5 p.m. on weekends, which is probably related to the peak of one-way trips between 1 and 4 p.m., as many e-scooters are in demand for charging. Reallocation trips mainly occur in the morning between 6 and 8 a.m. and in the evening between 10 p.m. and midnight. This temporal pattern can be reasoned by the following: (i) After most trips have been completed during the day and demand drops significantly, the e-scooters can be reallocated at night without disrupting business operations. (ii) in the morning, the e-scooter demand hotspots can be prepared by reallocation services, which can still respond to short-term changes (e.g., unexpectedly many scooters gathering due to a big event). Reallocation trips have the longest average distance of all trip categories.

Spatiotemporal Analyses

Land use data from OpenStreetMap (OSM) was consulted to conduct spatial analyses. It includes the five land use types: *residential, recreation, commercial, public transport, and public area.* The total size and their relative share per land use type can be found in [59]. All trip origins and destinations were assigned to a land use type. It enabled various analyses to be carried out. On the one hand, the temporal use patterns per land use type were created. This is illustrated in the left bar chart in Figure 18. Here, hourly trips were aggregated by origin, destination, weekday, and weekend. Apparently, on weekdays, the number of arrivals on public transport increases between 6 and 8 a.m. This observation can be attributed to commuter trips. This conclusion is consistent with the observation that arrivals

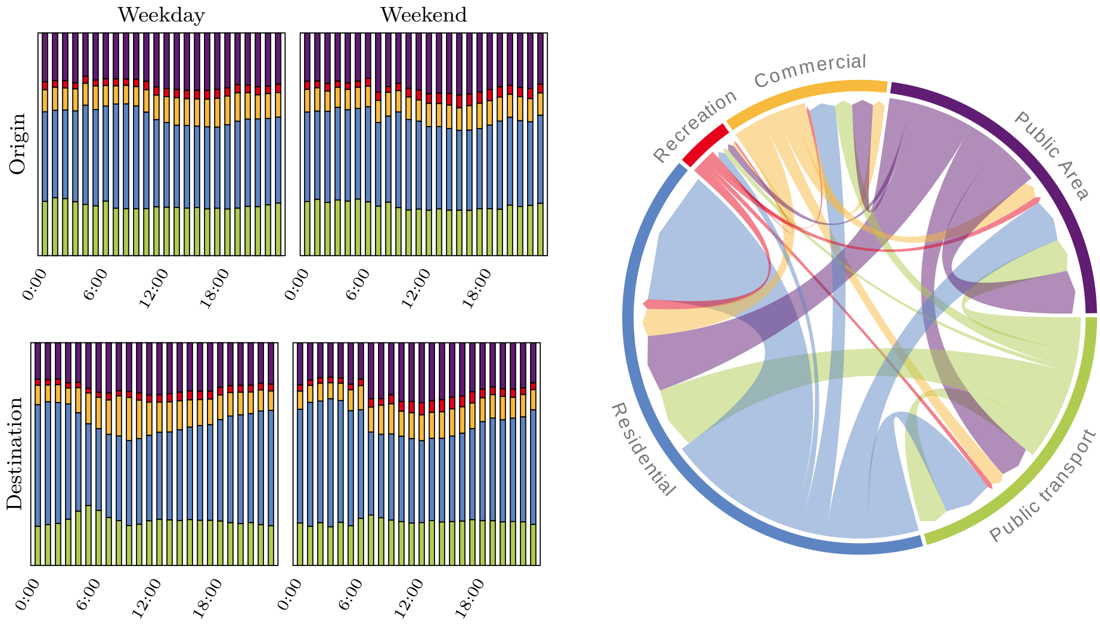


Figure 18: Temporal land use distribution of trip origins and destinations (left) and the corresponding connection in a chord diagram (right).

increase from the afternoon onwards in residential areas.
On the other hand, a chord diagram was used to show the traffic flows between the five land use types. This is represented in the right chord diagram. The division of the outer ring reflects incoming and outgoing trips. Each arrow's width indicates the number of trips from one land use type to another. Although public transport areas account for only 2.2% of the total, 20% of all trips arrive and 22% depart from there. In contrast, public areas, with an area share of 38%, record only 24% and 21% of all origins and destinations, respectively.
The further spatiotemporal analysis includes cluster analysis based on an HDB-SCAN algorithm. Then a velocity analysis of destination clusters is performed. In addition, nine POIs from the three public transport, sights, and commercial categories are analyzed in more detail concerning their temporal usage patterns. The similarity of the temporal usage patterns of these nine POIs is quantified using a cosine similarity analysis. This analysis measures similarity using a value between zero and one. Here, zero stands for no similarity, and one for the highest similarity. Except for *Checkpoint Charly* and *Kurfürstendamm*, all POIs show high similarity values with over 0.9. Despite the Cosine similarity analysis, a precise categorization of POIs is challenging because all POIs offer mixed uses (e.g., public transit, shopping, business, and industry).

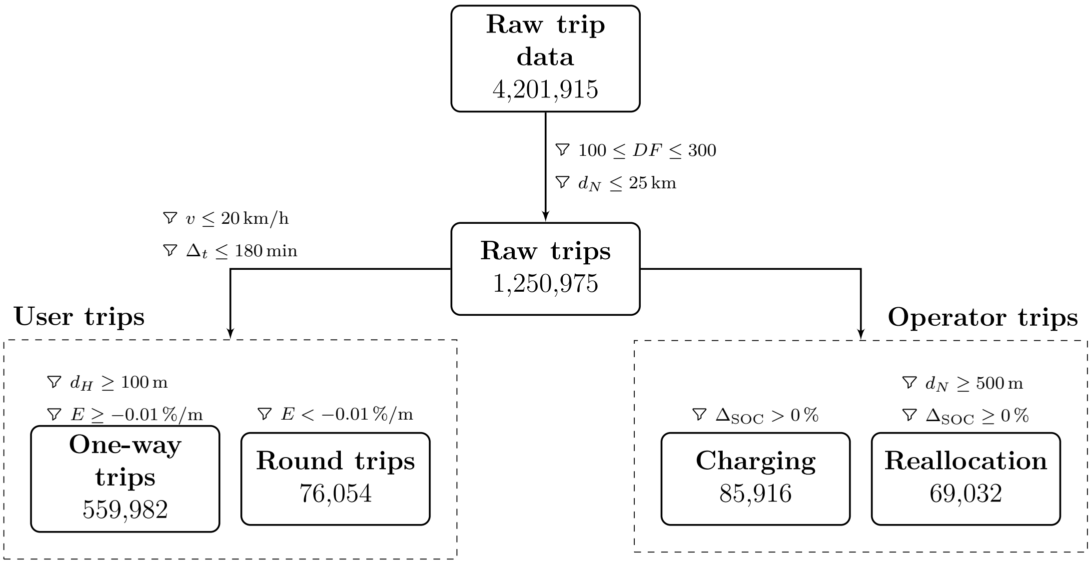


Figure 19: Trip filtering and categorization.

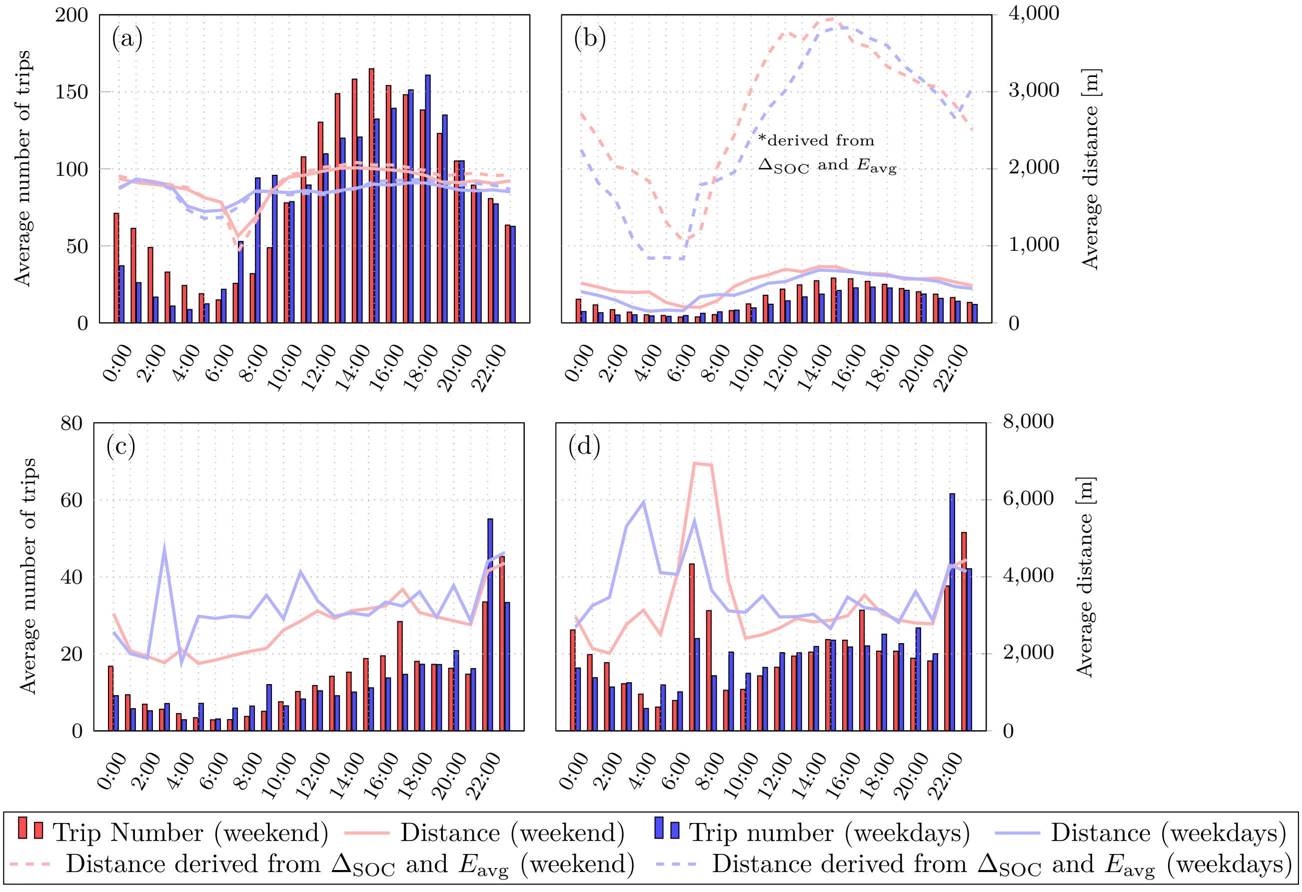


Figure 20: Trip numbers and distances of (a) one-way trips, (b) round trips, (c) charging, and (d) reallocation.

3.1.2 Retrospective on Contributions, Limitations, and Impact

A brief history of the article is provided to evaluate the contributions and impact of this article more comprehensively. We initially submitted the article to the special issue *Understanding and planning shared micro-mobility* of the peer-reviewed journal *Transportation Research: Part D Transport and Environment* in on 01.10.20. It has a two-year IF of 7.04. The journal took our manuscript under review with four reviewers. After two revisions, we submitted our manuscript a third time on 01.04.2021. On 25.05.2021, we received the final rejection from the journal because one of the four reviewers continued to oppose the publication of the manuscript. Then, we submitted the article to *Springer's* Q1 *Transportation* journal. After three and a half months of our submission not going through a review process, we withdrew the manuscript from the journal.

Finally, we submitted the manuscript to the journal *Sustainability* from *MDPI* publisher on 15.10.2021. The article was published after one round of revision on 12.11.2021. The article has been cited eight times since then (as of 21.11.2022). Although it has taken over a year to publish the article, and in parallel, the body of related literature has grown, there is a recognizable impact on the research community. The most important contributions are summarized in the following. First, it was one of the European region's first spatiotemporal analyses of e-scooter usage. Second, using the transparent representation of our data pipeline, we documented an approach and data processing steps to harness location data from e-scooters. Third, for the first time, we incorporated the phenomenon of round trips into data filtering and used our large dataset to demonstrate that the proportion of these trips is not negligible. Fourth, we demonstrated a more location-precise clustering considering the built environment by applying an HDBSCAN algorithm. Previous approaches were mostly based on spatial grids (e.g., hexagons), which have weaknesses due to their rough granularity.

However, there are significant limitations that must be highlighted. For the most part, API queries were performed at five-minute intervals. This means that trips of less than five minutes may be underrepresented. Furthermore, calculations of the average trip duration are distorted. E-scooter origin or destination data cannot be used as evidence of a specific rider's intention. We can derive assumptions and interpretations about trip intentions and destinations based on the temporal and spatial concentration of data points. However, the data are not evidence. All further limitations are outlined in [59].

3.2 Factors Influencing the Usage of Shared Micromobility: Implications from Berlin

This section aggregates the article *Factors influencing the usage of shared micromobility: Implications from Berlin* (Appendix A.6) written by Maximilian Heumann, Tim Brauner, Tobias Kraschewski, and Michael H. Breitner [62]. The article is currently in the second round of peer review at *Elsevier's Travel Behaviour and Society* journal. According to SJR rankings, it is a Q1 journal in the social sciences area of transportation and has a 2-year IF of 5.85. This article represents an extension of our work in [59]. This time, we compared three micromobility modes using the dataset from [59] but extended it significantly. We aim to provide a more comprehensive view of micromobility usage in Berlin and examine the influences of current events, such as the ongoing Covid-19 pandemic or the ever-growing micromobility fleets. To this end, we have developed a research design similar to that used in [59]. First, we show the current state of the literature on comparative studies of micromobility. Then, we elaborate on our data pipeline from acquisition, cleaning, and enrichment to analysis. From this, we elucidate our negative binomial regression model, present the results, and discuss conclusions for practice and research.

3.2.1 Summary of Contents

In the last three years, many spatiotemporal studies on micromobility usage have been published from different world regions. The North American region is the most widely presented (e.g., [121–129]). In contrast, regions such as Southeast Asia (e.g., [130]) and Europe (e.g., [59, 119]) are less represented, and other regions (e.g., South America, Africa) are not represented in high-ranking transportation journals.

All these studies contribute to a better understanding of micromobility from a scientific and practical perspective. Data-driven measures (e.g., the spatial distribution of vehicles, geo-fences, fleet size planning, and vehicle parking areas) can be implemented with the help of these studies. Other scholars (e.g., [131, 132]) argue that weather and fleet size growth are not fully understood in different regions. Micromobility users are particularly exposed to weather, and therefore only a few studies (e.g., [133]) have been published on the impact of weather on micromobility. With this study, we aimed to contribute to a better understanding of these issues and addressed the following research question:

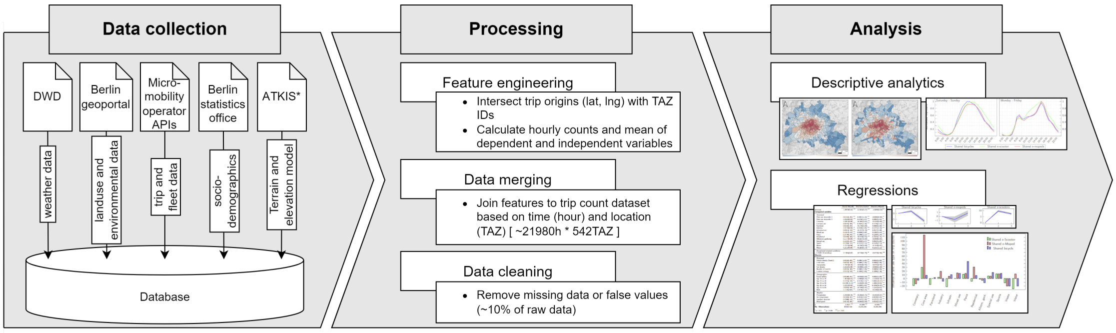
> *RQ: How is shared e-scooter, bicycle, and e-moped use affected by spatiotemporal weather, COVID-19, demographic, and fleet size-related variables in Berlin?*

In our systematic literature review, we identified 30 related studies. We classified these in table form according to research methodology, the foundation of data, dimensions (spatial/temporal), and other features. The table is in [62]. From the literature review results, we concluded that we have provided the first study to investigate the hourly effects of environmental-, fleet size-, vehicle density-, Covid-19 lockdown-, and temporal-related variables on e-scooter, e-mopeds, and bicycle use. Our study only included free-floating concepts to avoid comparative errors with station-based (docked) systems. Furthermore, we perceived different results on the influence of Covid-19 on the trip volume in the literature. Here, mainly the period of the underlying data was decisive. We also addressed this issue with our multi-year data set from September 2019 to March 2022.
The overall architecture of our research design and data pipeline is presented in Figure 21. We first extended the e-scooter trip dataset from [59] with trip time series of shared e-mopeds and bicycles to generate a longitudinal dataset. The descriptive statistics of the three micromobility modes dataset are summarized in Table 8. Here μ represents the mean and σ the standard deviation. OD refers to an origin-destination pair, which in turn represents a trip.

Table 8: Descriptive statistics of micromobility trip data collected in Berlin from September 2019 to March 2022.

Micromobility concept	OD* route distance [m]		Speed [km/h]		Average number of trips per hour		Total number of trips
	μ	σ	μ	σ	μ	σ	
Shared bicycles	2,202	859	7.5	1.9	101	91	2,172,650
Shared e-scooters	1,662	470	6.8	1.7	227	272	4,897,844
Shared e-mopeds	3,728	752	9.4	1.7	68	69	1,455,550

Moreover, we added hourly weather time series from the German Weather Service [134]. We then spatially resolved this temporal dataset to 542 traffic analysis zones (TAZs) provided by the Berlin Senate Department for Urban Development, Building, and Living. Our data analysis included a descriptive part on temporal and spatial characteristics and the application of a generalized linear regression model with a negative binomial distribution. A regression model of this type has



**Official Topographic Cartographic Information System, [137]*

Figure 21: Research design and data pipeline.

been used in related trip count analyses [127, 135]. We rejected using a Poisson model because we discovered over-dispersion for our dataset. According to [136], this would have resulted in a biased standard error and incorrect test statistics. Further details on the specification of our negative binomial model can be found in [62].

The following summarizes the selected results of the descriptive part and the regression analysis. First, we aggregated and normalized the hourly trip counts of the three modes. We have differentiated between weekdays and weekends. The temporal patterns of e-scooter use from our previous study, shown in Figure 20, were confirmed. The use of e-mopeds and bikes showed a similar pattern. A comparison of the three modes revealed that e-scooter trips increase more significantly than e-moped and bike trips on weekdays between 10 a.m. and 4 p.m. Using the unique vehicle identification numbers (IDs), we tracked the fleet sizes of the three modes over the entire period. We have presented the temporal trends of the absolute and relative fleet sizes in Figure 22.

This descriptive analysis provided evidence that the fleets of all three modes have steadily increased over the last three years. E-scooters and bicycles, in particular, recorded enormous growth in short periods. This result justified the incorporation of this variable into our negative binomial regression model. We subdivided each fleet size development graph into three tertiles to include fleet sizes as a categorical variable in the regression model. Using the temporal fleet development patterns shown in Figure 22, three time periods (tertiles) were formed and integrated as categorical variables. The tertile details regarding lower and upper limits can be found in [62]. For the categorical variable, this means that if a trip occurred in a certain temporal tertile, it is assigned the value one.

Table 9 summarizes all categorical and discrete variables. The results of the NBMs for the three micromobility modes are also documented in this table. Incidence rate ratios (IRRs) are plotted in parentheses beside the estimates. The IRRs represent a multiplicative effect. Values below one thus represent a negative effect, while IRRs above one signal a positive effect size. Selected results for the categorical and discrete variables are discussed below. A more in-depth and detailed discussion can be found in [62].

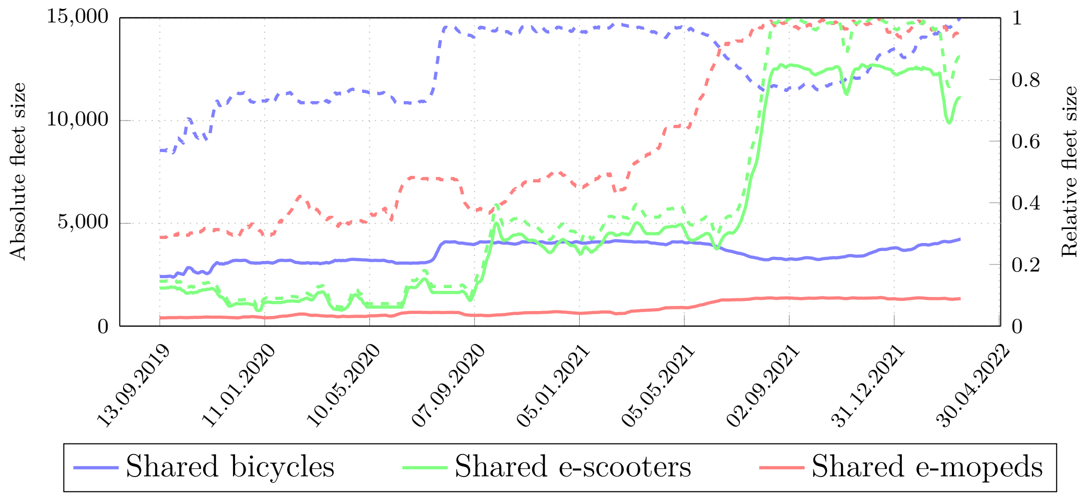


Figure 22: Estimated daily fleet sizes (lines) and normalized relative daily fleet sizes (dashed lines) of the considered micromobility operators.

Results and discussion

In the following, selected results of negative binomial (NB) regression models are presented and discussed. Temporal and weather variables are addressed first. Regarding temporal seasonal effects, shared bicycles and e-scooters were found to have a significantly more fluctuating trip volume than e-mopeds. While e-moped use varies by only ±5 % over an entire year, bicycle and e-scooter trips vary by as much as 30 % to 40 %. Similar trends were evident when examining Covid-19 lockdowns on the three micromobility modes. While bicycle and e-scooter trips decreased by 13 % to 21 %, e-moped trips decreased by only 2 %. Other literature (e.g., [138]) has measured the effects of Covid-19 lockdowns at up to 50 % reduction. Our results showed a lower effect in Berlin.

Among the weather variables, precipitation emerged as the variable with the most negative effect on micromobility use. 1 mm of additional precipitation reduces e-scooter and bicycle trips by 25 % and 24 % percent, respectively. In contrast, e-moped rides are reduced by only 13 % when the precipitation arrives. This difference can be due to helmet use, available gloves, and better protection from the e-moped front. The most negatively impacted are e-scooter trips. It can be due to the following aspects: (i) Many worldwide studies uniformly confirm that e-scooters are predominantly used for recreational activities. In particular, these ventures are constrained by precipitation. (ii) Furthermore, users might estimate the risk of accidents with e-scooters on wet roads to be higher than with e-mopeds. The other weather variables, such as air temperature, sunshine, and wind strength, recorded only marginal effects between 1 % and 2 %.

Furthermore, structural factors of the urban environment and concept characteristics were discussed. The bar chart in Figure 6 shows how the different land use types affect the number of trips of the three micromobility modes. Swimming lakes that are located outside the urban area have a positive influence on e-moped use. Due to motorization, higher speed than e-scooters, and seat comfort, e-mopeds are much more suitable for such activities. Bike-sharing differs from the other two modes in its versatility of use. The variable land use entropy, which quantifies the diversity of land use types in a TAZ, positively affects bike-share trips. Parks and sports facilities, in particular, positively influence bike-share trip volumes. Interestingly, the topography variable has a negative impact on non-motorized modes, as uphill terrain makes travel more difficult.

As mentioned above, the temporal fleet development of each mode was included as a categorical variable. Interesting effects could be discovered here. While the e-scooter fleet was increased once by 21 % and once by as much as 64 %, there was only an increase in trips of 10 % and 7 %. Saturation effects can explain this disproportionality. Parallel fleet expansion by competitors causes operators to cannibalize each other. These results are in line with [132]'s observations. In contrast, e-moped usage is stagnating around ±5 % with fleet size steadily increasing. Since this weak effect on e-mopeds is clearly distinguished from the effects on e-scooters and bicycles, e-mopeds can be regarded as an independent mode distinguished from the other two modes by unique characteristics.

3.2.2 Retrospective on Contributions, Limitations, and Impact

This research article is currently under peer review in the *Journal of Transport Geography* and, thus, has not been published so far. Therefore, no statements can be made about the contributions in a scientific or practical context. In [62], all

Table 9: Coefficients and (IRR) of the NB regression model.

	Shared Bicycles	Shared E-Scooter	Shared E-Mopeds
Intercept	-1.9478***	-1.3135***	-1.6096***
Categorical variables			
Structural			
Fleet size tertile 2	0.0192(1.02) ***	0.0917(1.10) ***	-0.0080(0.99) **
Fleet size tertile 3	-0.0680(0.93) ***	0.0704(1.07) ***	0.0083(1.01) **
Cemetery	-0.0453(0.96)	-0.2101(0.81) ***	-0.1520(0.86) ***
Corearea use	0.0825(1.09) ***	0.2621(1.30) ***	0.7728(2.17) ***
Farmland	0.0258(1.03)	-0.1736(0.84)	0.0000(1.00) ***
Industry	-0.0739(0.93) **	0.0346(1.04) ***	0.1771(1.19) ***
Infrastructure	0.0991(1.10) ***	-0.2477(0.78) ***	0.0577(1.06)
Mixed use	0.1287(1.14) ***	0.0026(1.00)	0.1382(1.15) ***
Parcs	0.3774(1.46) ***	0.1066(1.11) ***	0.1289(1.14) ***
Residential	0.0784(1.08) ***	-0.0739(0.93) ***	0.2679(1.31) ***
Allotment gardening	-0.1173(0.89) ***	-0.0137(0.99)	-0.0494(0.95)
Special use	0.1505(1.16) ***	0.0650(1.07) ***	0.0623(1.06) *
Sports	0.1286(1.14) ***	0.1174(1.12) ***	0.1185(1.13) ***
Waste	-0.2221(0.80)	-0.1207(0.89) ***	-0.2134(0.81)
Water	-0.2215(0.80) ***	-0.3183(0.73) ***	0.1161(1.12) ***
Exceptional temporal conditions			
COVID-19 lockdown	-0.1406(0.87)	-0.2336(0.79) **	-0.0224(0.98) ***
Discrete			
Structural			
Vehicle density	0.0008(1.00) ***	0.0007(1.00) ***	0.0018(1.00) ***
Land price	0.0338(1.03) ***	0.0574(1.06) ***	0.0293(1.03) ***
Topography	-0.2472(0.78) ***	-0.0638(0.94) ***	-0.0255(0.97) ***
Car traffic density	-0.0010(1.00) ***	-0.0011(1.00) ***	-0.0032(1.00) ***
Number of tourists	0.0389(1.04) ***	0.0517(1.05) ***	0.0323(1.03) ***
Landuse entropy	0.9163(2.50) ***	0.3893(1.48) ***	0.3096(1.36) ***
Demographics			
Welfare recipients	0.0054(1.01) ***	0.0004(1.00) ***	0.0025(1.00) ***
Age 18 to 24	-1.9036(0.15) ***	-1.4963(0.22) ***	-1.1347(0.32)
Age 25 to 34	0.1775(1.19) **	0.1176(1.12) **	2.8081(16.57) ***
Age 35 to 44	2.5739(13.11) ***	-1.2819(0.28) ***	1.4891(4.43) ***
Age 45 to 54	-0.0801(0.92)	0.5049(1.66) ***	4.5994(99.42) ***
Age 55 to 64	2.0388(7.68) ***	-0.7596(0.47) ***	2.1542(8.62) ***
Male	1.1126(3.04) ***	1.6726(5.33) ***	-0.1200(0.89)
Weather			
Precipitation	-0.2689(0.76) ***	-0.2816(0.75) ***	-0.1422(0.87) ***
Air temperature	0.0145(1.01) ***	0.0135(1.01) ***	0.0230(1.02) ***
Sunshine duration	0.0118(1.01) ***	0.0069(1.01) ***	0.0035(1.00) ***
Wind speed	0.0016(1.00) *	-0.0063(0.99) ***	0.0103(1.01) ***
α	0.2627 ***	0.3289 ***	0.2426 ***
No. Observations:	10,612,416	10,628,288	10,664,496

* $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$

limitations of this study are presented. The most important ones are discussed in the following. First, the same significant limitation arises as in [59]'s research article. Mobility data were queried and collected at five-minute intervals. This means that short trips, in particular, cannot be adequately recorded. Despite many data cleansing steps and preservation of data quality, it cannot be entirely ruled out that false trips were completely excluded. Furthermore, it must be clarified that three micormobility modes are being investigated by three operators in Berlin. This does not cover the entire micromobility spectrum. Nevertheless, this comparative study is one of the first in this context. The *Journal of Transport Geography* represents a prestigious outlet in the geographical dimensions of mobility. Due to the extensive data foundation and the results that do not exist in this form, the authors hope to achieve a relevant impact on the scientific micromobility community and practitioners working in this field.

3.3 Web Content Mining Analysis of E-scooter Crash Causes and Implications in Germany

This section summarizes the article *Web content mining analysis of e-scooter crash causes and implications in Germany* (Appendix A.5) [60]. Tim Brauner wrote the article as the first author with the co-authors Maximilian Heumann, Tobias Kraschewski, Oliver Prahlow, Jan Rehse, Christian Kiehne, and Michael H. Breitner. The article has been published in *Elsevier's* peer-reviewed journal *Accident Analysis & Prevention*. According to *Scimago's* journal rankings, *Accident Analysis & Prevention* ranks as a *Q1* journal in the subject area Engineering, Safety, Risk, Reliability, and Quality [40]. In Social Sciences, Human Factors and Ergonomics, *Accident Analysis & Prevention* is placed second among all outlets and has a 2-Year IF of 6.38 [39].

3.3.1 Summary of contents

The widespread distribution and use of shared e-scooters are accompanied by increasing numbers of accidents involving them. [24] confirmed in their accident analysis in the U.S. that widespread use increases the potential for danger and risk to e-scooter riders and other traffic participants. According to the Federal Statistical Office, accidents involving e-scooters doubled from 2020 to 2021 in Germany [25]. Despite this negative trend, in-depth accident analyses are scarce in micromobility research because access to accident databases is limited for researchers and the public. We developed a web content mining process to automatically collect 1,936 police reports about e-scooter accidents from a payment-free press portal. In contrast to retrospective clinical studies (e.g., [139–141]) that identify injury patterns and severity, this enabled us to investigate accident causation and circumstances in more detail. Thereby, we addressed the following research question:

> *RQ: What are relevant causes and implications associated with e-scooter crashes in Germany?*

We conducted a systematic keyword-based literature search to consolidate the current research in accident analysis in micromobility. In addition, we conducted it to provide an overview of applied research methods in accident analysis. At that time, we found 21 related studies. These studies could be divided into three categories based on their data. Most of the studies (e.g., [139, 141]) were in the clinical research field and investigated emergency department patients after an e-scooter accident. Second, we identified studies (e.g., [142]) that analyzed the riding behavior of e-scooter riders based on surveys and traffic observations. Third, we identified studies that used other data sources such as social media (e.g., [143]), print media (e.g., [24]), or insurance data (e.g., [144]). Although clinical studies have the highest relevance in accident analysis, their retrospective examination of injuries and their severity does not cover the entire spectrum. The reasons for the accident and the sequence of events can thus remain hidden [145].
Our research design included conducting a systematic web content mining process (e.g., [26]) followed by sentiment and network analyses and visualization using a clustering algorithm. The steps of our web content mining approach and data processing details from resource finding to analysis are shown in Figure 23.

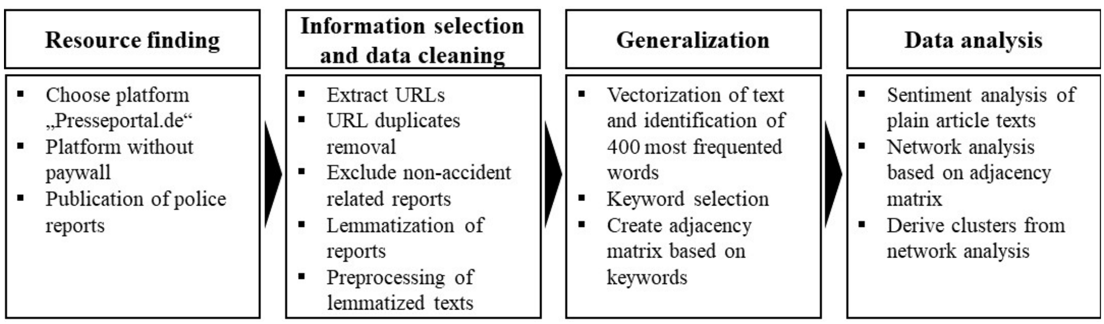


Figure 23: Systematic web content mining process.

The resource finding included a keyword-based search for relevant articles related to e-scooter accidents on the selected platform. We used the articles' collected unified resource locators (URLs) to extract their body texts automatically. Then, we filtered out irrelevant articles, such as those with unfitting headlines. Furthermore, we lemmatized the texts (removing stop words, reducing to the root word, etc.). Subsequently, we identified the 400 most frequented keywords in all articles using vectorization. This data foundation was used to conduct a sentiment and network analysis.

We carried out a sentiment analysis of all article texts using *Python*-based sentiment classifying algorithm of [27]. This sentiment classification algorithm uses a lexicon database from the open-source natural language toolkit (NLTK). When utilizing lexical sources, NLTK is one of the most common libraries [146]. We used sentiment analysis to check the article texts for possible distortions, dramatizations, or emotionalizations.

To visualize relationships in the dataset, we performed a network analysis of the most significant keywords. For this, we used the open-source graph and network analysis software *Gephi* from [28]. *Gephi* includes the network algorithm *ForceAtlas2* which we used to create our network graph. To better understand interrelationships in a network graph, it is best practice to reveal the communities within a network [147]. Therefore, we applied the *Louvain* algorithm to our network graph. This algorithm aggregates communities while maximizing the modularity parameter. Modularity represents the most widely used measure to evaluate the division of a network [29].

Based on the web content mining process in Figure 23, we collected $2,560$ police reports from April 2019 to May 2022. We cleaned this dataset of non-crash articles, which excluded 624. This has led to the final dataset of $1,936$. The temporal course of the published articles is shown in Figure 24. The sentiment analysis revealed a mean value of the polarity of all article texts of -0.05. This result shows mainly neutral coverage of police reports. Also, it demonstrated that the police reports have a high degree of objectivity and that there is a factual description of the incidents.

As mentioned above, we have identified the 400 most frequent keywords. We reduced the 400 keywords to 46 because many of them have not contributed to answering our research question. Then, we transferred these 46 keywords into an adjacency matrix, which indicates how often one keyword was used with another in an article. The adjacency matrix represented the input file for the *ForceAtlas2* algorithm and generated a network with 46 nodes and $1,952$ edges. The entire net-

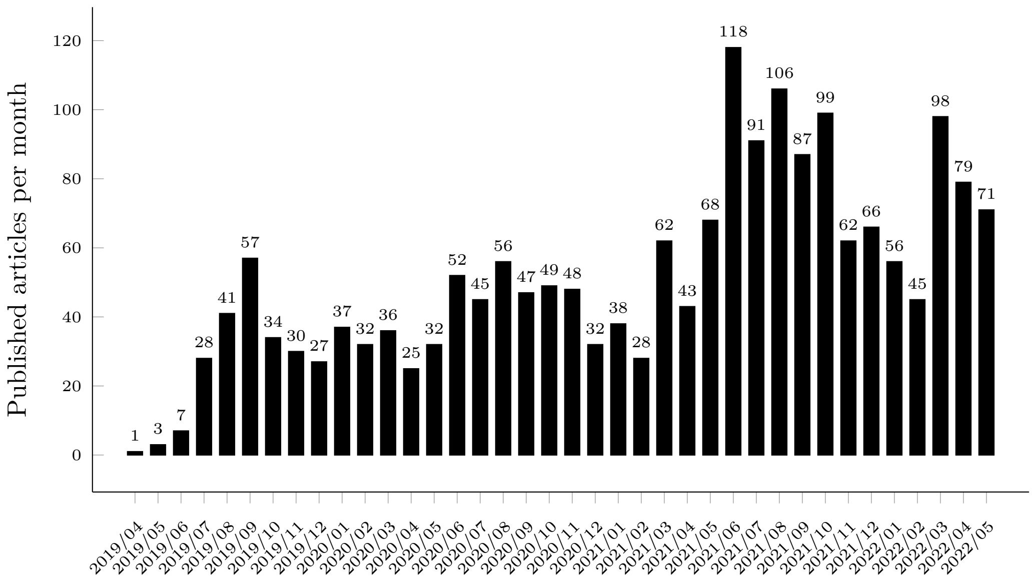


Figure 24: Published e-scooter crash-related police reports per month.

work with the four communities (clusters) is shown in Figure 25. The frequencies of the 46 keywords and their cluster affiliations can be found in [60].
Based on Figure 25, we discussed the network analysis results and formulated five recommendations to increase traffic safety, particularly for e-scooter riders. These five recommendations are summarized in condensed form below:

1. Consumption of drugs, especially alcohol, represent the major risk for e-scooter crashes. In areas with intense nightlife, the availability of shared e-scooters should be reconsidered. In Oslo, Norway, it has been shown that a nighttime e-scooter ban can positively impact (crash reduction) [148].

2. Two riders on one e-scooter is a common problem and poses a significant risk. We recommend equipping e-scooters with sensors to detect the number of riders to prevent this hazard.

3. Most e-scooter riders need to be more experienced and aware of which traffic areas they can use. E-scooter-related traffic signs can mitigate this uncertainty.

4. Although German e-scooter provider Tier Mobility offer helmet compartments on their vehicles, our study showed that helmet use has almost no relevance in crashes. This should be perceived as an alarming sign, and consideration should be given to mandatory helmet use.

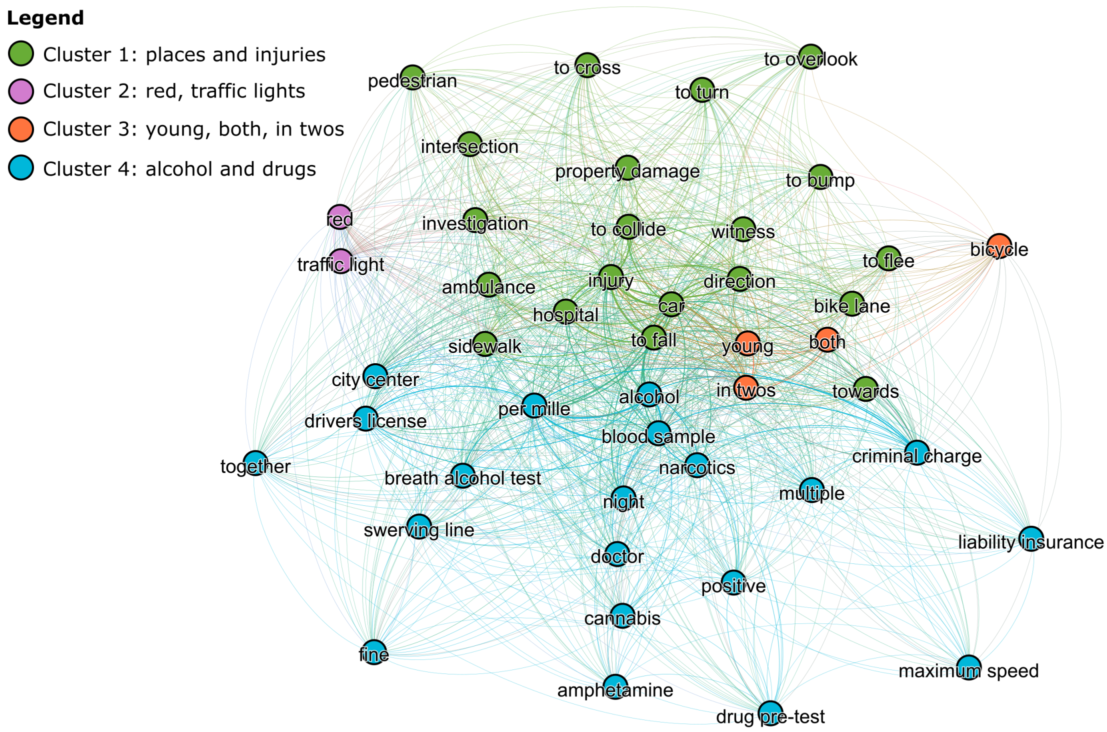


Figure 25: Network graph of 46 keywords and four communities visualized with *Gephi* using *ForceAtlas2* and Louvain algorithm [28].

5. Echoing the third recommendation, our data analysis revealed that approximately half of the e-scooter crashes occurred without the involvement of other traffic participants. This substantiates the inexperience of the drivers, which is why we propose introducing a riding education program.

3.3.2 Retrospective on Contributions, Limitations and Impact

The following are retrospective thoughts on the article's contributions, limitations, and impact. The dataset and the methodological approach to data analysis represent the significant contributions of this article. As confirmed by our literature review, results of clinical studies from emergency departments have been predominantly published to date to identify injuries, severity, and potential causation of accidents involving shared e-scooters. In particular, these studies can identify injury patterns and vulnerable body parts and quantify injury risks. However, to conduct a more comprehensive accident analysis, there needs to be more context and information about the circumstances of accidents. We discovered through our literature review that other data resources (e.g., social media) have rarely been used and published for e-scooter accident analysis. Thus, there is essential information potential in harnessing police reports of e-scooter accidents. These reports represent largely neutral, factual information about the accident process. Our dataset includes $1,936$ police reports over multiple months, providing an essential contribution to e-scooter accident analysis that has not been previously published on this scale.

The conjunction of web content mining, sentiment, and network analysis represents a methodological approach that has not yet been employed in micromobility accident analysis. To the best of our knowledge, this approach has yet to be used in accident analysis at all. Network analysis, in particular, can be used to visualize complex relationships in a large amount of data comprehensibly. Thus, this methodical approach can also be applied to other accident analyses, such as cars or bicycles. We hope to have provided a stimulus and inspiration for further accident analysis research. However, two limitations must be highlighted. First, the reduction of the 400 most relevant keywords to 46 was based on subjective evaluation by several researchers. Although the selection was aligned with the research question, this step in the methodology cannot be considered robust. Second, the network in our analysis achieved a relatively low modularity value compared to networks from different literature. This indicates that the distinction between the four communities could be more substantial. Higher modularity would have been desirable to enhance the network's interpretability. The potential impact of this article on the research community is difficult to assess at this time due to the recent publication. One article citation has been recorded since its publication in December 2022.

4 User-centric Design, Development, and Evaluation of an Individual Digital Study Assistant for Higher Education Institutions

This chapter comprises the article *User-centric Design, Development, and Evaluation of an Individual Digital Study Assistant for Higher Education Institutions*, which was written by Christin Karrenbauer, Tim Brauner, Claudia M. König and Michael H. Breitner (Appendix A.7). This article was published in journal *Educational Technology Research and Development* from *Springer Publishing* in June 2023 [57]. According to the journal's metrics, it has a 5-year IF of 5.61 in 2021

[43]. SJR lists this journal in the Q1 section in the subject area of social sciences and education [44].

4.1 Summary of contents

The number of lecturers and administrators has stagnated in recent years, while the student population has continued to grow and new academic programs have been developed [30]. Thus, a need for 1st, 2nd, and 3rd level support for students at higher education institutions (HEIs) has arisen. This trend has intensified, especially during the Covid-19 pandemic. Consequently, characteristics such as intrinsic motivation, self-organization, and self-regulation have become even more significant for successful studies. However, acquiring these characteristics is perceived as demanding and challenging by students [32]. Additionally, [31] confirmed that a high degree of self-regulation competencies positively influences HEI graduation. Starting from this problem, digital study assistants can address the lack of support options and thus enable students to succeed.
Based on Action Design Research (ADR) from [56], we consolidated requirements for an individual digital study assistant (IDSA) from various HEI stakeholder groups and developed and field-evaluated a prototype. We addressed the following research question:

> *RQ: What requirements guide a user-centric design and development of an IDSA?*

In the digital transformation, many forms of virtual assistance have emerged at HEIs recently. These include, for example, educational conversational agents (chatbots). While such assistance systems have often focused on subject-specific learning, we distinguished the goals of an IDSA from this. We defined that an IDSA strengthens self-regulation skills, goal achievement planning, and study organization through suitable functionalities. This conceptual focus arose from the realization that these factors significantly influence successful graduation [31, 149]. A user-centric IDSA primarily addresses students, but other stakeholders, such as lecturers and organizational leaders, must also be considered when developing an IT artifact. The interaction between the development, utilization, and evaluation of an IT artifact by several stakeholders is reflected in the fundamental idea of ADR proposed by [56]. Our four-stage ADR process, including tasks and outcomes, is summarized in Table 10.

As mentioned in Table 10, we derived design requirements based on qualitative and quantitative analysis and literature. We identified a total of seven requirement categories with 32 characteristics. A detailed description of all characteristics can be found in [57]. From the requirements, we developed an IDSA prototype within six months. In weekly SCRUM sprints, we incorporated the requirements into the IDSA artifact and iteratively evaluated them with various stakeholders (e.g., lecturers, researchers, and organizational leaders). In Figure 26, we have visualized the overall architecture of the IDSA system. A few core ideas are presented in the following, which underlie architecture development. To enhance the factors of user-friendliness, usability, and utility, we integrated the IDSA into an already existing learning management system (LMS). By connecting the IDSA with an LMS, it was possible to leverage essential resources (e.g., course information and students' background information on their studies) that provided the data foundation for the functions of the IDSA. Due to an important demand for multifunctionality formulated by students, we have designed the IDSA with eight functionalities. The contents and purposes of the functionalities are outlined in more depth in [57]. Furthermore, a key idea of the IDSA's backend was to establish interfaces that enable external resources, such as open educational resources (OERs) to be accessible.

We had rolled out the IDSA at three HEIs, and 1,036 users initially tested it. Due to high data security and privacy requirements, users were empowered to decide how their data would be used when the IDSA was initially installed. This has led to data from only 634 students for evaluation purposes. Nevertheless, we were able to evaluate all eight functionalities, and, in addition, we were made aware of program errors that could be improved afterward. Further details on the evaluation of the IDSA are elaborated in [57].

We explained and contextualized the emerging issues and experiences of the project team during the development and testing phases. We have documented the findings and research results in the form of design knowledge according to [150].

4.2 Retrospective on Contributions, Limitations and Impact

Since this research article is under revision and has not yet been published, no statements can be made about the contributions and impact. This article was ini-

Table 10: Action Design Research phases, tasks, and outcomes.

Stage	Task	Outcomes
Problem formulation	Identify, articulate, and conceptualize a research opportunity.	Due to the increasing student number and constant HEI staff, there is a lack of student support. Courses and content become increasingly diverse, whereas student biographies become more individualized. IDSA can support students and have a positive impact on self-regulation.
	Formulate an initial research question	What requirements guide a user-centric design and development of an IDSA?
	Identifying theoretical bases and prior technology advances	We reviewed IDSA literature to identify typical unique selling propositions and accordingly formulated design and development requirements.
	Secure a long-term commitment	Researchers participated in all stages of the development process and beyond.
	Define roles and responsibilities	Our ADR team included researchers from IS, cognitive science, information management, business management, digital teaching, campus management, and higher education didactics. Researchers' tasks were divided into conception, design, and development of the IDSA.
Building, intervention, and evaluation	First selection of participants.	We conducted a student survey with 570 students from three German HEIs.
	Further selection of participants.	We interviewed 19 lecturers and 9 employees of a German HEI organizational unit to analyze the practical perspective.
	Ongoing iterative development, testing, and evaluation.	We derived requirements qualitatively, quantitatively, and from literature. Parallel, we developed our IDSA prototype based on our requirements engineering. ADR researchers and selected students continuously tested it. The prototype has been launched for a three-month test phase in 2021.
Reflection and learning	Ongoing formalization and discussion of requirements for an IDSA in HEI.	We compared our findings with recently published papers. We formulated advanced requirements that must be considered during IDSA design and development.
	Submissions to workshops/ conferences for academic and practical feedback.	We published and discussed findings at conferences and workshops between mid-2019 and early 2021 for discussions with IS and HEI administration and management experts.
	Analyze the intervention results according to the research objects.	Compared to our research goals, we formulated further requirements for an IDSA design and development.
	Describe the organizational outcomes.	We discussed organizational changes necessary for HEI with associated experts.
Learning formalization	Abstract results to a class of field problems.	Through our multi-perspective requirements and subsequent prototype evaluation, we abstracted generalizable requirements.
	Focus on transferability of results and communication of outcomes.	We triangulated our results and findings. With our findings, we transferred our outcomes and deduced recommendations for HEIs.
	Specify the outcomes.	We considered the results and findings of all data for requirements and recommendations of an IDSA design and development.

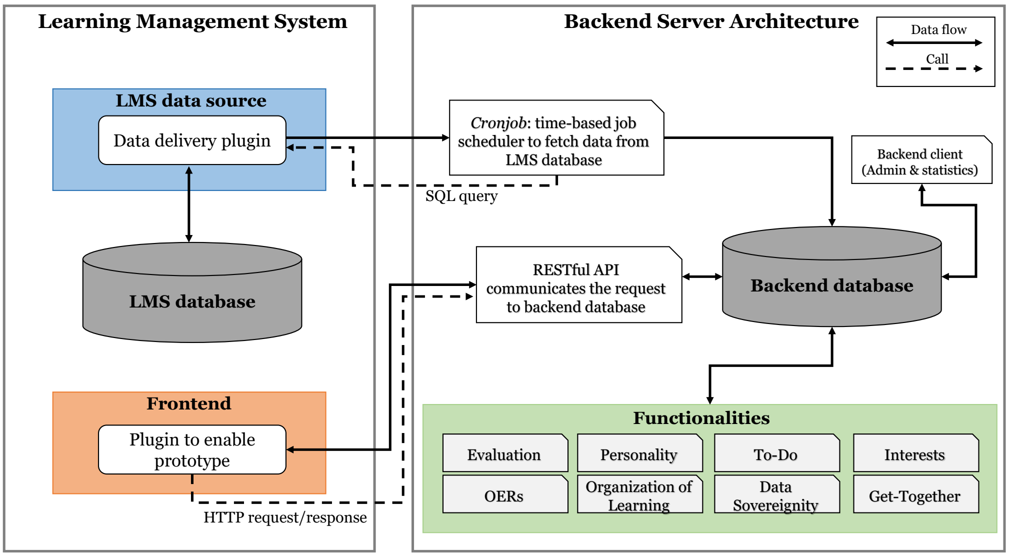


Figure 26: IDSA prototype system architecture.

tially submitted to ICIS 2022 in the track *Digital Learning and IS Curricula* and received a mostly positive review. Unfortunately, the Associate Editor rejected the article at the time because of one self-reference. Nevertheless, the authors used the feedback and suggestions for improvement and submitted the article in an enhanced version in the current journal. After the first review, the authors received a major revision with three reviewers. Despite many points of criticism, the three reviewers confirmed its relevance for the field of education technology research. The most significant limitation of this research article lies in developing the IDSA prototype. The development process became complex due to the involvement of many different stakeholders from different research disciplines and multiple locations. Due to high data protection requirements, the evaluation of the prototype was restricted, and the research results ultimately suffered from that. Nonetheless, the ICIS reviewers and the journal of *Educational Technology Research and Development* mostly appreciated the sample size and results of the student survey and expert interviews with HEI stakeholders. The derived requirements for IDSAs and prototype development were found to be valuable for the scientific community.

5 Final Appraisal and Outlook

This final chapter first discusses the strengths and weaknesses of all nine research articles. Next, the *NESSI* and Shared Micromobility Research pillars are reflected in more detail, as they are the heart of this dissertation. Subsequently, the research articles from Sections 2.5 and 4 are discussed and retrospectively evaluated. Issues and challenges during research processes and data analyses are elaborated. All follow-up research questions are summarized in Table11.

General Reflection on this Dissertation

All research articles in this dissertation either address practice-related issues from the energy and mobility sectors or present the development and evaluation of an IT artifact in the form of DSS or assistance systems. In particular, research articles 2.1 to 2.3 and 4 resulted in the creation of software artifacts to be applied to support real-world decision-making and upcoming challenges.
When creating extensive IT artifacts, there are usually many stakeholders and, thus, diverse objectives. Different objectives lead to constant changes (improvements) in the IT artifact or DSS structure. Established research methodologies such as DSR and ADR were applied to develop prototypes, IT artifacts, and comprehensive DSS. These approaches were particularly well suited in that they are design-oriented and flexible. DSR offers iterative development and evaluation steps that can be conducted over a more extended period, leading to a more efficient artifact. The other research articles (2.4, 2.5, and 3.1 to 3.3) address real-world issues or phenomena. Established research methodologies such as morphological analysis, regression analysis or cluster algorithms were applied. These research methodologies, statistical metrics, and algorithms were particularly appropriate for understanding relationships more profoundly and visualizing research results understandably.
From this reflection, these nine research articles' general strengths and weaknesses can be derived. Pressing problems such as climate change are addressed, and *NESSI* is presented as a comprehensive and mature DSS that can contribute at least in a modest way to tackling climate change. The two research articles on MGs and transparency in the German PV market also address essential issues in the energy sector and provide tangible and applicable results for stakeholders from academia and industry. The three research articles from the field of shared micromobility investigate the phenomenon of still-young shared concepts in urban areas. Here, deep analyses based on extensive datasets are conducted to understand temporal and spatial use. In addition, risk factors and causes of accidents are examined in more detail. All these results of the nine research articles in the

Table 11: Outlook and further research questions.

Domains	Sections	Further Research Questions
Decision Support Systems, Energy Informatics, and Energy Economics	2.1 - 2.3	Which design elements of *NESSI* can be generalized and used by other DSS? How can general design guidelines for energy model systems and DSS be derived from the DSR project *NESSI*? What factors strengthen the widespread use of environmental (energy-related) DSSs from academia? Through what channels should inexperienced potential users learn about *NESSI* so that effective use occurs and real action is taken?
	2.4	How can the morphological box be developed toward an MG project guideline?
	2.5	Can PV market transparency be enhanced by an open-access platform? What positive and negative effects does a public platform have on market participants and consumer behavior?
Shared Micromobility Research	3.1 - 3.3	How can location-specific insights into micromobility usage be gathered despite high data protection standards? What are fleet expansion's economic, ecological, and social effects in urban areas? How do individual safety measures (ban on e-scooters at night, mandatory test drives) affect the occurrence and severity of accidents?
IDSA	4	How can IDSA be tested more specifically in the field? Which criteria can be used to quantify the impact of IDSA on students' self-regulation? Which student groups are the main users of IDSA?

form of DSS and findings represent strengths in their entirety. However, especially from an academic point of view, it is also necessary to reflect on the missing elements of this dissertation. No article extends an existing research methodology or process model. Although methodologies are adapted and tailored to research questions, there is no methodological extension beyond that. Furthermore, it has yet to be feasible to formalize generalizable design principles that can emerge in developing IT artifacts. The nine research articles did not reach this meta-level. For the sake of fairness, however, it must be mentioned that all research articles were focused on high practical relevance and real-world decision-making.

Reflection on the DSR project *NESSI*

The following reflects on the more than four-year DSR project *NESSI*. The core idea of *NESSI* has been well-fitting into the calls from the Green IS community (e.g., [4, 5]) since the project started. *NESSI* addresses the complex transformation of buildings towards emission-free energy supply. It is one of the key sectors that can reduce global CO_2 emissions on a significant scale. However, after more than four years contributing to this project, some challenges and shortcomings must be emphasized so that future research can learn from those.

The issue of addressing too many stakeholders

In general, DSR-guided DSS strive to reach high efficacy which in turn means high applicability for relevant stakeholders. As *NESSI* addresses mainly stakeholders outside the research community, the aspect of complexity reduction becomes important. *NESSI's* kernel belongs to the domain of energy system models which is a saturated research field for years. *NESSI* uses known energy (component) models and combines them in a unique ranking-based energy flow simulation. This kind of procedure has been done in countless energy models and tools, and thereby represents no novelty for the energy research discipline. The unique selling point of *NESSI* stems from its out-of-the-box applicability for inexperienced stakeholders by making complex energy system analysis accessible and understandable. In particular, the out-of-the-box characteristic is highlighted by scholars in energy model research as relevant to success [12]. The *NESSI* project faced great challenges in striking the balancing act between scientific relevance and practical applicability. Scientific outlets in energy research have often criticized the lack of theoretical contribution. However, practical applicability and decision-making support for stakeholders were the focus. This property of *NESSI* can only be achieved by reducing the complexity of the underlying energy models.

This dilemma has given rise to an idea for *NESSI*. Due to the diverse requirements of the stakeholders, stakeholder-adapted versions of *NESSI* needed to be considered. With more customized versions for stakeholders, more valuable, efficient, and understandable solutions can be created. However, this direction entails challenges. On the one hand, stakeholder adaptation results in a high development effort. Second, *NESSI* lost one of its initial principles, which was to be accessible to everyone.

The issue of lacking relevance within the (Green) IS community

NESSI itself and parts of it were published at established IS conferences, such as AMCIS 2019, ICIS 2020, HICSS 2022, and in the journal *Building and Environment*. The conference presentations, proceedings, and journal outlets should have created visibility and relevance of *NESSI*. However, regarding citations within the (Green) IS and energy research community, *NESSI* can be considered to have low relevance. The reasons for this are discussed in the following. Although established Green IS scholars (e.g., [4, 5, 49]) have been calling for solution-oriented research related to climate change for over a decade, it is difficult to position DSS artifacts like *NESSI* in the top tier journals (basket of eight) of the IS discipline. Basket of eight journals partly acknowledged the importance of solution-oriented research addressing climate change, but there is scarce room to publish such studies. Some Green IS-related special issues and articles were published [151–153]. However, in general, top tier journals are mainly theory- and methodology-driven and this can hardly be provided by solution-oriented DSR projects which result in artefacts.

However, the difficult positioning of *NESSI* in top tier journals should not be an excuse for the lack of relevance. Achieving this should be a major part of future *NESSI* research. The practical relevance of *NESSI* should always be in the foreground, as it has always been about the transformation of the building sector and thus indirectly addresses climate change mitigation. It should be mentioned here that in recent years *NESSI* has already been presented at many exhibitions, fairs, and public talks by the development team. Feedback from stakeholders from industry and citizens could thus be obtained, and the practical relevance increased. Table 11 under point 2.3 presents questions relevant to further research and the DSR project *NESSI*.

Reflection on MG Research

The research in 2.4 represented the first essential steps toward systematizing MGs. The morphological box could be applied to the categorization of numerous real MGs. Since the planning and development of MGs involves many stakeholders, further research should try to include relevant stakeholders in the extension of the morphological box. Thus, the morphological box's layers, dimensions, and characteristics would be validated more extensively and practically. The morphological box could add practical value if applied as a guideline for future MG projects. Relevant stakeholders could use it as a checklist to include the essential elements of MGs adequately. These considerations lead to a further research question in Table 11.

Reflection on PV Market Transparency

The research and results in Section 2.5 have shown that PV system market prices depend on numerous factors, and spatial differences are not easily explained. Significant spatial price differences are opaque and difficult to understand, especially for private decision-makers. The methodological approach and analysis procedures from the research work in 2.5 laid the foundations for creating a potential platform for price comparisons of residential PV systems. Future research can accompany the systematic development of such a platform. In addition, such a platform's positive and negative effects on market players must be examined. For this purpose, RQs are formulated in Table 11.

Reflection on Shared Micromobility Research

In the following, the strengths and shortcomings of the three research articles 3.1 to 3.3 are critically reflected. While the article-specific limitations have already been mentioned, an overall assessment of the three articles is developed. Spatiotemporal studies are highly dependent on data quality. In articles 3.1 and 3.2, micromobility datasets from Berlin were collected and used, which stand out from many related studies (e.g., [121, 122, 124]) due to the long period and the number of data points. A crucial point of all micromobility studies is the data basis. While driving data was accessible for many American studies through prepared portals, the accessibility of such data in Europe is severely restricted. Such portals do not exist. In addition, data protection regulations prohibit recording trajectory data of micromobility vehicles. Here, the shortcoming of articles 3.1 and 3.2 lies. Only with raw location data, no traveled paths can be traced. Therefore, a routing machine was used that simulated the shortest route. As a result, it was not possible to derive conclusions on highly frequented streets, sites, and bottlenecks that can exist. From this, the direction for the first continuing research question arises. How can location-specific insights into micromobility usage be gathered despite high data protection standards?
The analyses of the research article in 3.2 revealed that the fleets of all micromobility modes have steadily grown, especially the e-scooter fleet has increased dramatically. Despite fleet expansions of up to 100%, the number of trips made

with micromobility modes has increased by only 7 to 10%. This dilemma has already been discussed and contains significant challenges for cities worldwide. Urban space is scarce, and fleet expansions exacerbate this already existing conflict. Not without reason, some German cities have already started drastically restricting shared e-scooter use. Further micromobility research can examine fleet expansion's economic, environmental, and societal effects in more depth. Despite a high degree of technology openness, an optimum should always be created for urban citizens. Finding this optimum and achieving it with appropriate measures can be part of future research. All micromobility-related research questions are listed in Table 11.

Reflection on IDSA Research

Last, there is a reflection on IDSA research. Known limitations and challenges encountered have already been explained in 4.2. The motivational background and purpose of IDSA are to support students in completing their studies. Successfully completing the studies requires not only subject-specific but also generic skills. In particular, IDSA addresses interdisciplinary skills such as self-regulation, but the effects cannot be validly quantified due to a lack of field tests and empirical findings. The elicitation of requirements for IDSA and implementation in practice in 4 represented the first important steps. However, there is still room for improvement for further research. Further IDSA RQs are formulated in Table 11.

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A Appendices

A.1 Decision Support for Optimal Investments in Building Energy Systems

Authors: Tim Brauner and Tobias Kraschewski

Outlet: Proceedings of the 25^{th} Americas Conference on Information Systems (AMCIS) 2019, Cancun (Mexico)

URL: `https://aisel.aisnet.org/amcis2019/green_is_sustain/green_is_sustain/5/`

Abstract: In 2000, the Renewable Energy Sources Act (EEG) initiated a large dissemination of photovoltaic systems in Germany. The EEG guaranteed a fixed feed-in remuneration for 20 years, which is highly profitable for many private and commercial prosumers. Feed-in tariffs have decreased substantially, resulting in a different economic situation for prosumers. Current prosumers that are about to exit the remuneration in the near future facing the challenge of readjusting their energy infrastructure. Whereas, potential prosumers aiming to establish an efficient building energy system. Both need an artifact that introduces the idea of efficient investments in renewable energy sources technology. Our decision support system (DSS) seeks to provide guidance for private and commercial prosumers by simulating small energy systems, presenting performance indicators and thereby display investments' impact on the building energy system's efficiency. The Green IS based DSS reduces complexity of components and enables prosumers to follow a sustainable transformation path.

Keywords: Decision Support System, Building Energy System, Efficiency, Energy Prosumer, Sustainable Transformation.

A.2 Transformation to Sustainable Building Energy Systems: A Decision Support System

Authors: Tobias Kraschewski, Tim Brauner, Sarah Eckhoff, and Michael H. Breitner

Outlet: Proceedings of the 41^{st} International Conference on Information Systems (ICIS) 2021, Hyderabad (India)

URL: https://aisel.aisnet.org/icis2020/societal_impact/societal_impact/2/

Abstract: The sustainable transformation of the building sector is one of the biggest levers to achieve global climate protection agreements. Therefore, individual decisions regarding building energy systems (BESs) become more important and building stakeholders require tangible options to create an energy-efficient and renewable-energy-based building stock. Our research aims to address this problem and presents a decision support system based on a software engineering approach that follows the guidelines of the design science research methodology and seeks to provide guidance for investment decisions in BESs by highlighting technical, economical, and ecological performance indicators. The computational study evaluates the performance of various scenarios regarding costs and CO2 emissions for different buildings. Our results contribute insights for the design of future BESs and provide building stakeholders with a holistic view to tackle conflicting objectives and to follow a sustainable transformation path.

Keywords: Transformation of Building Energy Systems, Decision Support System, Design Science, Green IS, Energy Informatics.

A.3 Classification of Real-World Microgrids Based on a Morphological Analysis

Authors: Jana Gerlach, Sarah Eckhoff, Oliver Werth, Tobias Kraschewski, Tim Brauner, and Michael H. Breitner

Outlet: Proceedings of the 27th Americas Conference on Information Systems (AMCIS) 2021, Montreal (Canada)

URL: https://aisel.aisnet.org/amcis2021/green_IS/sig_green/5/

Abstract: Microgrids integrate distributed energy resources into an energy network reliably and efficiently. However, research of real-world examples at the international level is limited. We conduct a morphological analysis for microgrid design options to examine the status quo of academic literature. We identify 18 dimensions with 60 characteristics divided into the five layers governance, business, intelligence, communication, and physical. Subsequently, we classify 30 real-world microgrids with diverse types and locations using our morphological box. Our analysis reveals future research requirements regarding social aspects, business models, critical success factors, and maturity levels. We provide a framework supporting decision-makers to identify microgrid design options and promote socially, economically, and environmentally sustainable, resilient, and decentralized energy supply.

Keywords: Real-World Microgrids, Morphological Analysis, Classification, Future Research Agenda.

A.4 A Spatiotemporal Study and Location-Specific Trip Pattern Categorization of Shared E-Scooter Usage

Authors: Maximilian Heumann, Tobias Kraschewski, Tim Brauner, Lukas Tilch, and Michael H. Breitner

Outlet: Sustainability

DOI: https://doi.org/10.3390/su132212527

URL: https://www.mdpi.com/2071-1050/13/22/12527

Abstract: This study analyzes the temporally resolved location and trip data of shared e-scooters over nine months in Berlin from one of Europe's most widespread operators. We apply time, distance, and energy consumption filters on approximately 1.25 million trips for outlier detection and trip categorization. Using temporally and spatially resolved trip pattern analyses, we investigate how the built environment and land use affect e-scooter trips. Further, we apply a density-based clustering algorithm to examine point of interest-specific patterns in trip generation. Our results suggest that e-scooter usage has point of interest related characteristics. Temporal peaks in e-scooter usage differ by point of interest category and indicate work-related trips at public transport stations. We prove these characteristic patterns with the statistical metric of cosine similarity. Considering average cluster velocities, we observe limited time-saving potential of e-scooter trips in congested areas near the city center.

Keywords: E-Scooter, Micro-Mobility, Shared-Mobility, Land Use Analysis, Spatiotemporal Analysis, Spatial Allocation, HDBSCAN, Big Data.

A.5 Web Content Mining Analysis of E-Scooter Crash Causes and Implications in Germany

Authors: Tim Brauner, Maximilian Heumann, Tobias Kraschewski, Jan Rehse, Oliver Prahlow, Christian Kiehne, and Michael H. Breitner

Outlet: Accident Analysis & Prevention

DOI: `https://doi.org/10.1016/j.aap.2022.106833`

URL: `https://www.sciencedirect.com/science/article/abs/pii/S0001457522002688`

Abstract: In Germany, police reports published via press are neither uniformly written nor accessible to the public. There is a lack of comprehensive and factual data-based analyses of e-scooter crashes and their causes. We collected 1,936 crash-related reports over two years via the German press portal based on a systematic web content mining process. Sentiment analysis results revealed that the police reports' coverage is predominantly factual and neutral and, therefore, useful for keyword-based analyses. After identifying the 46 most relevant keywords in the reports, we generated an adjacency matrix to investigate the keywords' dependencies, visualized the network and dependencies of the most relevant keywords, and categorized them into four thematic clusters using the Louvain algorithm. Our results and findings reveal that driving under drug influence, especially alcohol, is one serious problem. Riding e-scooter in pairs and on forbidden terrain or in the wrong direction are also common causes of crashes. Consequences for e-scooter riders are severe injuries, driving license revocation, fines, criminal charges, and incurring for property damage. Further, wearing protective gear and helmets is of low acceptance among the e-scooter ridership. Based on our results and findings, we recommend e-scooter bans during the night times for some locations, obligatory driving tests before first e-scooter use, and helmet wearing.

Keywords: E-Scooter, Accident Analysis, Web Content Mining, Sentiment Analysis, Network Graph.

A.6 Factors influencing the usage of shared micromobility: Implications from Berlin

Authors: Maximilian Heumann, Tim Brauner, Tobias Kraschewski, Lukas Tilch, and Michael H. Breitner

Outlet: Journal of Transport Geography
Status: Under review.

Abstract: The popularity of urban micromobility has steadily grown in cities worldwide. There is a lack of comparative studies investigating factors influencing the travel behavior of shared micromobility in Europe. From this, we investigate shared bicycle, e-scooter, and e-moped usage in Berlin based on trip data from September 2019 to March 2022. We incorporate a comprehensive set of spatial, temporal, weather-, fleet size-, and COVID-19-lockdown-related factors. To account for significant over-dispersion in our hourly resolved panel dataset for 542 traffic analysis zones, we specify a negative binomial regression model to estimate variables of trip counts for the three micromobility concepts. Our descriptive results reveal spatiotemporal characteristics of shared bicycle, e-scooter, and e-moped usage and significant growth of operating fleet sizes in Berlin in recent years. We provide evidence that fleet expansion will not result in proportionally more trips and competitive effects are evident. As urban space is scarce and regulations on fleet sizes are lacking, urban planners and service providers use these findings and complementary studies to plan fleets and their allocation optimally. Impacts associated with land use vary between concepts and allow for demand-based planning. Precipitation is the most impactful factor among the weather variables and shows a pronounced adverse effect on all three modes. COVID-19-lockdown phases had no significant effect on e-mopeds. While bicycles were moderately affected, e-scooter trips decreased significantly. The findings can help policymakers and micromobility operators further optimize sharing mobility services and facilitate evidence-based strategies for the spatial and temporal design of micromobility.

Keywords: Shared Micromobility, Negative Binomial Regression, Panel Data, Spatiotemporal Analysis, Fleet Size, COVID-19.

A.7 User-centric design, development, and evaluation of an individual digital study assistant for higher education institutions

Authors: Christin Karrenbauer, Tim Brauner, Claudia M. König, and Michael H. Breitner

Outlet: Educational Technology Research and Development

DOI: `https://doi.org/10.1007/s11423-023-10255-8`

URL: `https://link.springer.com/article/10.1007/s11423-023-10255-8`

Abstract: Increasing student numbers in higher education institutions (HEI), diverse educational biographies, and COVID-19 require more individual study support. Individual digital study assistants (IDSA) address these challenges with online, easy, ubiquitous, and automated access. Guided by Action Design Research, we design, develop, and evaluate an IDSA that, e.g., improves students' self-regulation competencies, study goals achievement, and study organization. Based on 28 qualitative HEI expert interviews, a quantitative survey with 570 students, and a literature review, we first derive general IDSA requirements. User-centered we then develop and evaluate our IDSA prototype tested by more than 1,000 students. It e.g., recommends lectures based on individual interests and competencies, offers matches with other students, or gives feedback about learning behavior strengths and weaknesses and can partly replace or supplement human 1^{st} level support. Our IDSA requirements offer HEI administrative and lecturers applicable knowledge and recommendations, support IDSA theory building, and show further research needs.

Keywords: Individual Digital Study Assistant, Higher Education Institution, Requirement Analysis, Prototyping, Evaluation, Action Design Research.

A.8 Disentangle the Price Dispersion of Residential Solar Photovoltaic Systems: Evidence from Germany

Authors: Tobias Kraschewski, Tim Brauner, Maximilian Heumann, and Michael H. Breitner

Outlet: Energy Economics

DOI: https://doi.org/10.1016/j.eneco.2023.106649
URL: https://www.sciencedirect.com/science/article/pii/S0140988323001470

Abstract: Although Germany has the largest capacity of installed residential photovoltaic (PV) systems in Europe, comprehensive evidence on transparent pricing information remains missing. This study disentangles why PV quote prices are subject to significant dispersion and analyzes which factors influence particularly low- and high-priced systems in Germany. We create a comprehensive cross-sectional dataset of 19,561 PV system quotes from 2011 to 2022 and use regression analyses to investigate the effects of system characteristics, installation scope, and location-related parameters on quoted prices. Our results reveal highly volatile annual price dispersion consistent over 11 years and large price differences despite similar system characteristics. Applying hedonic regression techniques, we reveal spatially fine-resolved price heterogeneities with up to 20 % difference in the German PV market. System characteristics such as battery usage, installation scope, and system capacity have the most significant effect sizes and are instead control variables. More insightful, the installer density shows price-lowering effects, whereas more PV installations per region, higher solar radiation, and higher labor wages cause price-increasing effects. Quantile regression results reveal that installer density promotes the price reduction of high-priced systems more. Scaffolding, AC installation, and elevation are significant price-increasing factors but with small effect sizes. Finally, DC optimizers affect the levels of high-priced systems more than low-priced ones.

Keywords: Residential Solar PV, Price Dispersion, Hedonic Model, Quantile Regression, Quote data.

A.9 Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Nano Energy System Simulator *NESSI*

Authors: Sarah Eckhoff, Maria C. G. Hart, Tim Brauner, Tobias Kraschewski, Maximilian Heumann, and Michael H. Breitner

Outlet: Building and Environment

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URL: `https://www.sciencedirect.com/science/article/abs/pii/S0360132323003232`

Abstract: The urgency of climate change mitigation, rising energy prices and geopolitical crises make a quick and efficient energy transition in the building sector imperative. Building owners, housing associations, and local governments need support in the complex task to build sustainable energy systems. Motivated by the calls for more solution-oriented, practice-focused research regarding climate change and guided by design science research principles, we address this need and design, develop, and evaluate the web-based decision support system *NESSI*. *NESSI* is an open-access energy system simulator with an intuitive user flow to facilitate multi-energy planning for buildings and neighborhoods. It calculates the technical, environmental, and economic effects of 14 energy-producing, consuming, and storing components of the electric and thermal infrastructure, considers time-dependent effects, and accounts for geographic as well as sectoral circumstances. Its applicability is demonstrated with the case of a single-family home in Hanover, Germany, and evaluated through twelve expert interviews.

Keywords: Energy System Simulation, Decision Support System, Open Access Web Tool, Renewable Energy, Design Science Research.