Essays on Decision Support for Sustainable Decentralized Energy Systems

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M. Sc. Sarah Eckhoff

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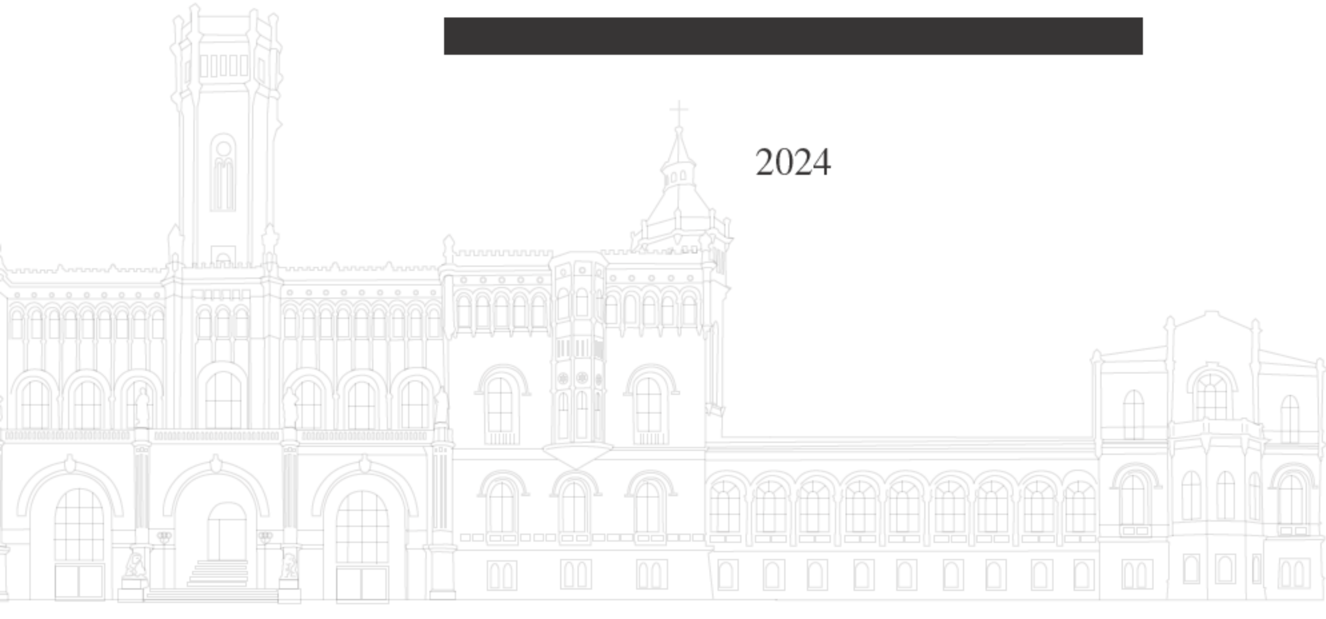

Betreuer und Gutachter:	Prof. Dr. Michael H. Breitner
Weitere Gutachterin:	Prof. Dr.-Ing. Astrid Nieße
Vorsitzender der Prüfungskommission:	Prof. Dr. Erk P. Piening
Weiteres Mitglied (beratend):	Dr. Ute Lohse

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Abstract

Information Systems Research can contribute in various ways toward society's sustainability transformation and thereby address the United Nations' Sustainable Development Goals. The essays in this cumulative dissertation use decision support for decision-makers in the building sector as a mean. Nine of the fourteen research articles concern the development of an energy system simulation tool called NESSI (Nano Energy System Simulator) that provides decision support for investment decisions in renewable energy technologies on the building and neighborhood level. Three essays contribute toward decision support for design options of microgrids. Another two articles can be summarized as decision support for electric vehicle integration into neighborhood power grids through distributed energy resources. Each of the research streams has resulted in a generalization that focuses on a theoretical contribution to accompany the more practice-focused research: For NESSI, design principles for the wider decision support system class were established; for microgrid design options, the research design was generalized and written up as a method paper; and the electric vehicle integration approach was written up as a method and published on the project's research platform.

Keywords: Decision Support Systems, Design Science Research, Energy Informatics, Green Information Systems

Zusammenfassung

Die Wirtschaftsinformatik kann auf verschiedene Weise zur Nachhaltigkeitstransformation der Gesellschaft und damit zur Erreichung der Sustainable Development Goals der Vereinten Nationen beitragen. Die Aufsätze in dieser kumulativen Dissertation verwenden Entscheidungsunterstützung für Entscheidungsträger im Gebäudesektor als Mittel. Neun der vierzehn Forschungsartikel befassen sich mit der Entwicklung eines Energiesystem-Simulationstools namens NESSI (Nano Energy System Simulator), das Entscheidungsunterstützung für Investitionsentscheidungen in erneuerbare Energietechnologien auf Gebäude- und Nachbarschaftsebene bietet. Drei Aufsätze leisten einen Beitrag zur Entscheidungsunterstützung für Gestaltungsoptionen von Microgrids. Zwei weitere Artikel lassen sich als Entscheidungsunterstützung für die Integration von Elektrofahrzeugen in Nachbarschaftsstromnetze durch verteilte Energieressourcen zusammenfassen. Alle Forschungszweige mündeten in einer Generalisierung, um die eher praxisorientierte Forschung mit theoretischen Beiträgen zu ergänzen: Für NESSI wurden Gestaltungsprinzipien für die größere Entscheidungsunterstützungssystemklasse aufgestellt; für die Gestaltungssoptionen für Microgrids wurde der Forschungsentwurf generalisiert und als Methodenaufsatz aufgeschrieben; und der Ansatz zur Integration von Elektrofahrzeugen wurde als Methode formuliert und auf der Forschungsplattform des Projekts veröffentlicht.

Schlüsselwörter: Entscheidungsunterstützungssysteme, Gestaltungsforschung, Energieinformatik, Grüne Informationssysteme

Management Summary

Introduction

The dependence on fossil fuels in the building sector, which provide 70 % of global demand, leaves players vulnerable to price changes, supply shocks, and political friction (Al-falahi et al., 2017; United Nations Development Programme, 2016). Furthermore, up to 3.5 billion people around the world do not have a reliable electricity supply and more than 700 million citizens have no access to electricity at all (Ayaburi et al., 2020). In accordance with the United Nations' Sustainable Development Goals (SDGs), these global needs can be addressed by the establishment and improvement of decentralized energy systems. Distributed renewable energy resources like photovoltaic and wind provide decentral and environmentally friendly power where it is needed and replace central, mostly fossil fuel-powered power plants (International Energy Agency, 2022). These renewable resources can be coupled with the heat and mobility infrastructure through heat pumps and electric vehicles to use even more of the self-produced electricity (International Energy Agency, 2022). Top-down efforts to foster the establishment and improvement of decentralized energy systems are slow and often encounter significant implementation challenges. The decision process and long-term projects' success require the participation of local citizens and, especially in developing countries, mechanisms to enable and promote cooperative action (Cherni & Kalas, 2010; Robinson & Imran, 2015). The Information Systems (IS) Research community has acknowledged this need and calls to use its "transformative power" to provide solution-oriented studies that address climate change (Gholami et al., 2016, p. 529). Therefore, the overarching research question of this dissertation is:

> *How can IS Research contribute to the transformation in the building sector toward sustainable decentralized energy systems?*

IS Research can contribute in various ways toward society's sustainability transformation. The essays in this cumulative dissertation use decision support for decision-makers in the building sector as a mean. Lehnhoff et al. (2021) explicitly state the value of Decision Support Systems (DSSs) that promote sustainable energy systems. The essays are structured into three parts. Nine of the fourteen research articles concern the development of an energy system simulation tool that provides decision support for investment decisions in renewable energy technologies on the building and neighborhood levels. Three essays contribute toward decision support for design options of micro-grids. Another two articles can be summarized as decision support for electric vehicle integration into neighborhood power grids through distributed energy resources.

Decision Support for Sustainable Buildings and Neighborhoods: The Nano Energy System Simulator NESSI

Stakeholders in the building sector, i.e., building owners, housing associations, and local governments around the globe, are confronted with conflicting goals of cost-effectiveness, energy resilience, and environmental friendliness while navigating the establishment and transformation of building and neighborhood energy systems (Eckhoff et al., 2023, see also A.9). We derived that they are in need of intuitive and easily accessible decision support for investment decisions in renewable energy systems that incorporates local circumstances. In addition, institutions that aim to support these efforts, like energy consultants, policymakers, and non-governmental organizations, are in need of adequate tools to support the decisions.

We developed the Design Science Research (DSR)-based DSS NESSI (Nano Energy System Simulator) that provides all the above-mentioned stakeholders with a scientifically rigorous energy system analysis tool, enables economically and environmentally sound decision support, and meets literature-, stakeholder-, and evaluation-based requirements. NESSI is an energy system simulator designed as an open-access, free web tool and currently available at https://nessi.iwi.uni-hannover.de/en/home. To account for various types of stakeholders and respective energy system sizes, NESSI analyses the energy supply for buildings (i.e., single family homes, multiple family homes, and commercial buildings) and neighborhoods. It offers decision support for investment decisions toward sustainable energy components through simulating the energy flows in buildings and neighborhoods with an hourly resolution, calculating cash flows and other economic indicators, greenhouse gas emissions, and a social sustainability score. It incorporates variations over time and a load profile generator.

NESSI's development began in 2018. Multiple design cycles were conducted to iteratively improve the software which culminated in various publications. Two research streams were pursued in terms of addressees. The main addressees of NESSI are located in developed nations such as Germany. Next to that, a specific focus was placed on stakeholders in developing countries. Publications were motivated by either of the research streams, i.e. stakeholders in developed or developing countries. Both research

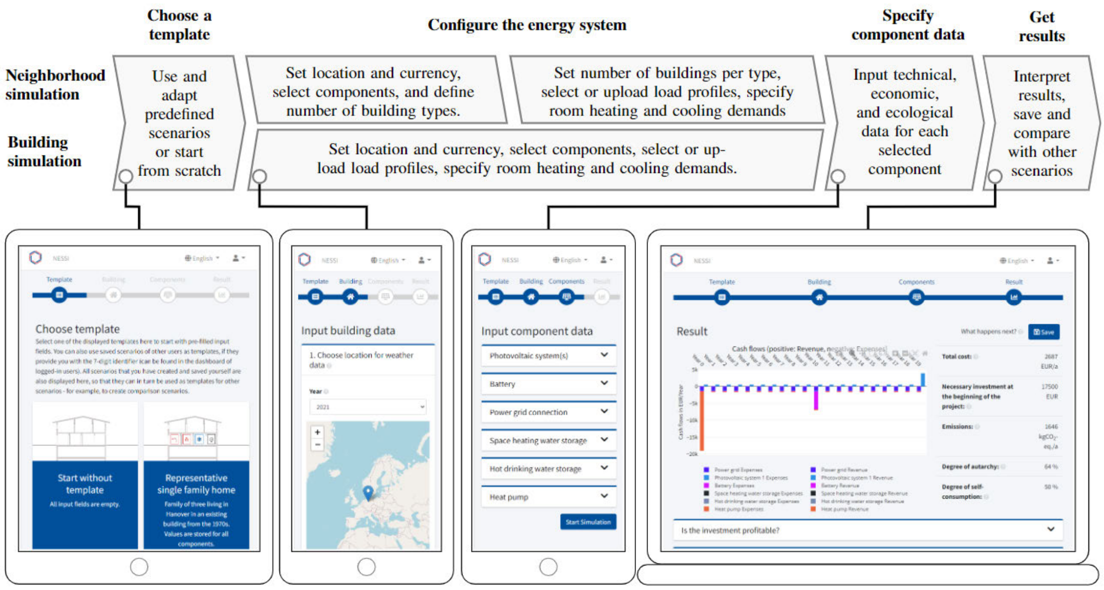

Figure M.1: User Flow of NESSI's Neighborhood and Building Simulation with Exemplary Screenshots of the Web tool on Various Devices (Eckhoff et al., 2023)

streams contributed to the same software tool. First, we started out in Matlab R2019b App Designer and presented the first prototype in Kraschewski et al. (2020, see also A.1). Afterward, we adapted the tool for usage in developing countries (Hart, Eckhoff, & Breitner, 2023b, see also A.8). Time-varying factors, such as demand changes, price volatilities, and component degradation highly impact energy system performance (Fioriti et al., 2021). Therefore, we implemented variations over time into the simulation (Eckhoff et al., 2022, see also A.4). To increase the accessibility, we implemented the DSS as a web tool and described the development process up to this point as one overarching design cycle. This was published in Hart et al. (2022, see also A.6), focusing on developing countries, and Eckhoff et al. (2023, see also A.9), focusing on the underlying architecture and simulation procedure. Figure M.1 shows an overview over the graphical user interface and user flow. For conducting case studies and the provision of exemplary load profiles, we used the load profile generator RAMP for developing countries by Lombardi et al. (2019) that requires programming knowledge. To facilitate load profile generation as part of NESSI, we implemented a graphical user interface for RAMP in Hart, Eckhoff, and Breitner (2023a, see also A.7), that is also referenced in Lombardi et al. (2023, see also A.14). Social sustainability is a key aspect to successful energy development projects (Evans et al., 2009). Ignoring social and cultural issues in the respective communities has proven to result in low local acceptance, leading to project failures in the long term (Urmee & Md, 2016). Therefore, we incorporated the social dimension into NESSI in Hart, Eckhoff, Schäl, et al. (2023, see also A.10). Lastly, we generalized our learnings during the five years of developing NESSI, to derive general design principles for bottom-up societal sustainability transformations in developing countries (Hart et al., 2024, see also A.13).

Decision Support for Microgrid Design Options

The calls of the United Nations' SDGs are also well reflected in the growing dissemination of microgrids as they enable the sustainable transformation of utility networks, organizations, and communities (Sachs et al., 2019). In the works of this dissertation on the topic of microgrids, we focused on electricity provision. Microgrids foster decarbonization in the energy sector due to their capacity to integrate distributed energy resources into distribution networks (Hirsch et al., 2018), offer economic benefits (Stadler et al., 2016) and can promote social benefits, particularly through electrifying remote areas (Briganti et al., 2012). Depending on the demands and goals of stakeholders and the environment, microgrids can be designed in numerous ways. For example, microgrids can be islanded or utility-grid-connected, and have centrally operated or decentralized energy management. The resulting extensive space of microgrid design options hinders their widespread dissemination. Before reaching out to consultants, microgrid-interested parties such as communal politicians and energy managers of residential and commercial building complexes require strategic decision support to identify suitable design options for their use case.

In a first step, we analyzed microgrid design options via a morphological analysis and classified real-world microgrids according to the resulting framework. The classification enables the revelation of viable and common design option combinations. This helps decision-makers such as building owners and energy grid operators to determine their current state and possibilities for future enhancements. This was published in Gerlach et al. (2021, see also A.2). Building on that, we derived a way to provide strategic decision support based on the conducted analyses. The idea was developed during the Americas Conference on Information Systems (AMCIS), where we participated in the invite-only Paper Development Workshop (PDW) to advance five promising papers toward journal publication through in-depth feedback from senior scholars and received one of the two Best Sprint Paper Awards. We used the morphological analysis of the previous paper and expanded the real-world microgrid data set by 32 new microgrids. Microgrid archetypes, an algorithm-based decision tree, and archetype-specific design

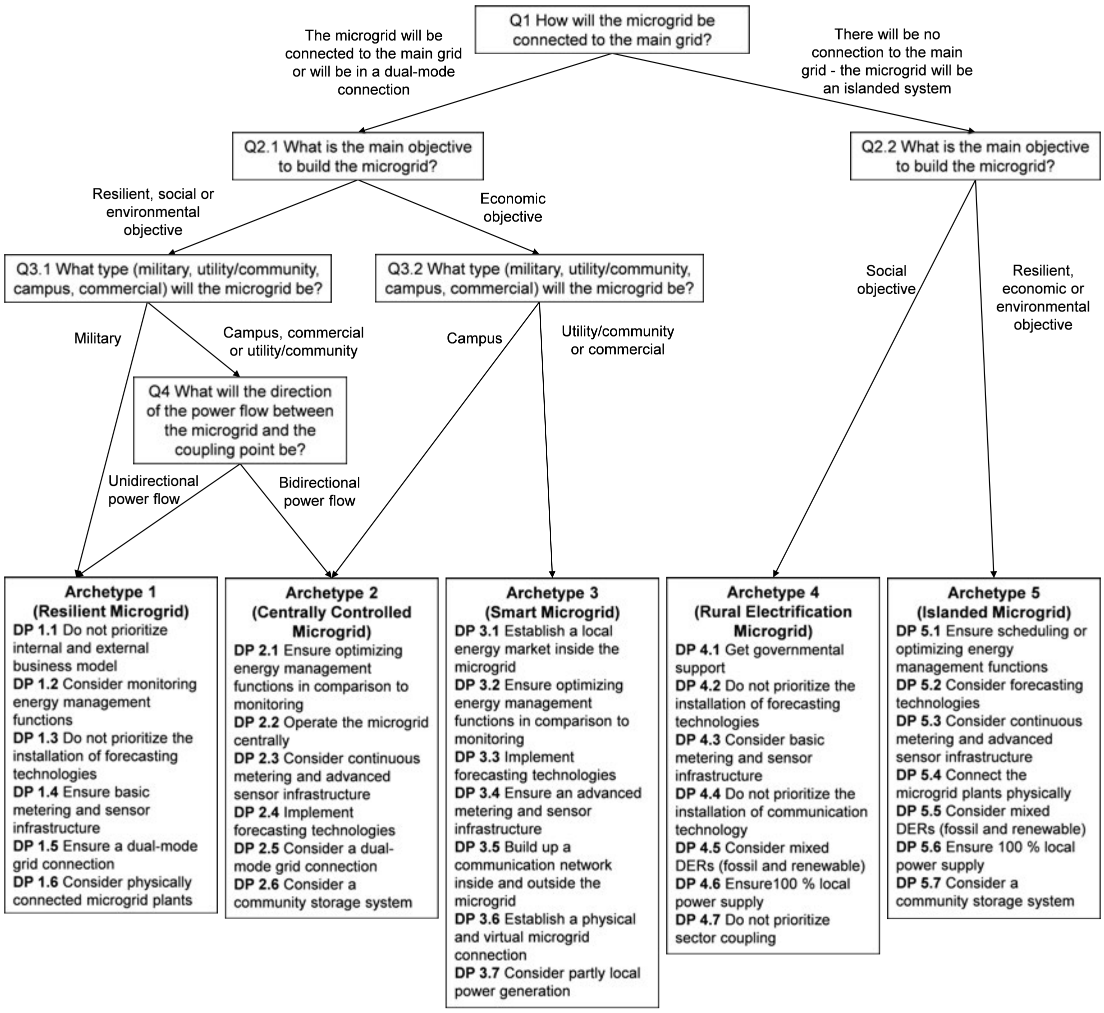

Figure M.2: Design artifact consisting of decision tree and design principles for microgrid design options (Gerlach et al., 2024a) principles were derived from the data set, see Gerlach et al. (2024a), A.11 and Figure M.2. The research provides applicable knowledge and a benchmark framework for researchers and enables comprehensive and simultaneously simplified decision-making in practice. The developed method was successfully applied to other domains, see Gerlach, Hoppe, et al. (2022) and Gerlach, Werth, et al. (2022), once using the taxonomy approach instead of the morphological analysis as classification framework. This inspired us to write down the research design as a general method paper. As the taxonomy method is more disseminated in the IS community, we used that method for the generalized research design, see Gerlach et al. (2024b) and A.12.

Decision Support for Electric Vehicle Integration in Neighborhoods

The call of the United Nations' SDG 13 (climate change mitigation) is also well reflected in the growing interest in low-emission mobility forms. Battery-electric mobility is the most promising post-fossil mobility form, as seen by the exponential increase in the number of electric vehicle registrations worldwide. In 2022, over 10 million electric vehicles were sold, amounting to 14 % of all new cars (International Energy Agency, 2023). As a result, both the infrastructure for charging and the number of charging sites must increase. The increased load from charging electric vehicles was not taken into account when constructing the electric grid of existing neighborhoods, which can nowadays cause violations of operational boundaries (Held et al., 2019). One approach to alleviate the grid's burden is grid-sided measures that enhance the grid capacity. These are effective but cost-intensive and require an intervention in the grid and its environment (Wagner et al., 2020). Instead, user-sided measures are promising that use the growing dissemination of distributed energy resources such as photovoltaic systems or batteries. In this context, the establishment of energy communities is beneficial. The term energy community is defined as multiple actors with a geographical connection that jointly consume, produce, and share renewable energies (Horstink et al., 2021). Energy communities are a crucial component in the vision of a sustainable European Union's energy system according to the Clean Energy Package of the European Union (European Comission, 2019). To support the decisions of communal planners and politicians as well as grid operators toward measures to ensure grid stability in the presence of numerous electric vehicles, the grid capacity needs to be examined in various scenarios.

In a first step, we examined the existing literature regarding electric vehicle integration into energy communities to identify trending topics and future research directions. This was published in Eckhoff et al. (2021, see also A.3) to serve as an overview of the chances and challenges associated with energy communities in the context of electric vehicles. We found a significant number of simulation models with similar aims. Therefore, we proposed the creation of an open-source simulation model to reduce parallel work and foster faster progress. Additionally, we proposed a meta-study of the existing models to synthesize the knowledge base. Building on those realizations, we set up an open-source co-simulation to analyze the impacts of an increasing electric vehicle penetration rate on the low-voltage grid. This was published in Wagner et al. (2022, see also A.5). The extendable co-simulation, including the energy system models, simulation scenarios, and input data, is publicly available and, thus, enables meta-studies. In contrast to the other two research directions that comprise this dissertation, this research direction was not explicitly framed as decision support at the time.

Contributions

The contributions to practice of the three research streams are more apparent than the theoretical contributions, as the goal was to conduct solution-oriented, practice-relevant research. Nevertheless, a particular effort was made to (simultaneously and ex-post) contribute to theory as well. NESSI assists the investment decision toward renewable energy technologies for building owners, housing associations, and local government. As byproduct, we generated a framework of social criteria and indicators for assessing the sustainability of energy systems which provides guidance for researchers and decision-makers. In terms of theoretical contribution, NESSI also serves as a research tool to conduct case studies (see, e.g., Hart & Breitner, 2022). The derived design principles represent nascent design theory in the categorization of Gregor and Hevner (2013) (level 2) that can serve as a basis for the development of a mature design theory. The presentation of NESSI at several public events resulted in regular users and interest from climate agencies and energy consultants. In February 2024, NESSI has 97 regular users who created an account while the number of users without an account is not measurable. Our microgrid decision support research strategically supports microgrid-interested parties to obtain an overview of microgrid design options. It supports stakeholders in preparing for discussions with a microgrid planner. We showed that IS Research can contribute to the discourse in microgrid literature despite it being

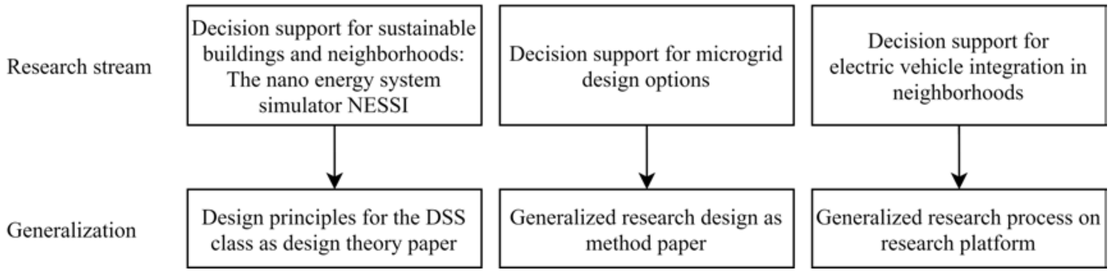

Figure M.3: Generalizations in this Dissertation

a more technical topic. We found only one other paper that deals with the topic from an IS perspective, Sachs et al. (2019). We enhanced their framework with applicable knowledge. While theirs only illustrates the possible dimensions of microgrid design, we examined the dependencies between design dimensions and highlighted important decisions at the beginning of a project and design principles. Norouzi et al. (2022, p. 5) recognized “an absence of structured knowledge in the domain of smart microgrids” and highlighted the “need for frameworks to reduce complexity in design”. We addressed this by providing a comprehensive and simultaneously simplified view of the dependencies between microgrid dimensions. Additionally, Seidel et al. (2017) called for more integration between research and practice in the Green IS field. Through the analysis of real-world microgrids, we integrated the practice perspective into the artifact prominently. The decision support artifact can also act as a starting point for further theory building, e.g. design theory or maturity models. Moreover, the developed research design can be applied to a huge variety of domains, even existing taxonomies and archetype analyses. Regarding the third research stream, the review paper provides a structured overview of academic knowledge on the topic of electric vehicle integration into neighborhoods that was missing beforehand, despite numerous publications. The follow-up paper addresses the revealed need for an open-source simulation suite to foster collaboration and transparency. Due to its modular structure, it is easily extendable.

Each of the research streams has resulted in a generalization: For NESSI, design principles for the wider DSS class were established; for microgrid design options, the research design was generalized and written up as a method paper; and for the electric vehicles in energy communities topic, the approach was written up as a method and published on the web-based research platform that was also developed, see Figure M.3. The two generalization research papers represent a contribution to theory building.