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Contributions to Web-based Simulation Software for Sustainable Energy Systems

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Abstract

Motivated by the calls for more solution-oriented studies that contribute to the energy transition, this dissertation comprises of ten articles describing the development, evaluation, validation, application, and abstraction of the multi-criteria decision support system NESSI. NESSI is an open-access, web-based software simulating energy systems for buildings and neighborhoods. Using an adapted design science research approach, NESSI is further developed in five consecutive design cycles specifically for actors in developing countries. For each design cycle, requirements were derived through systematic market research, literature analyses, user tests, and expert interviews. After extensive iterative programming works, each design cycle is demonstrated, evaluated, and validated by applying the software to suitable contexts in developing countries. Further methods to improve and validate NESSI included reviewer feedback as well as presentations at national and international events. Two articles describe extensive case studies situated in Thailand and Colombia to further demonstrate NESSI. This work led to a joint article, co-authored with an international project team, which presents the load profile generator RAMP and its integration into NESSI. Moreover, the functionality of the tool is introduced in a separate article to serve as a manual, to support transparency, trust, and credibility as well as to highlight the tool's global applicability. In the last article, nascent design theory is derived by formulating seven grounded design principles with multiple design features for the wider application of bottom-up societal sustainability transformation. Throughout this development process, it was proven that the decision support system NESSI supports bottom-up energy transition, educates stakeholders, and empowers people. Nevertheless, several limitations regarding the tool's restrictiveness are highlighted. Challenges during software development are elaborated on, especially in terms of the stakeholder definition, the remote research approach, the tool's complexity and credibility as well as importance of stakeholder networks. Stakeholders and researchers are invited to further improve NESSI, challenge the approach, and together develop a more refined model to foster the bottom-up energy transition.

Keywords: Simulation Software, Decision Support System, Design Science Research, Renewable Energy Systems, Developing Countries, Nascent Design Theory.

Zusammenfassung

Motiviert durch den Bedarf an praxisorientierten Studien für die Energiewende befasst sich diese Dissertation in zehn Artikeln mit der Entwicklung, Evaluierung, Validieren, Anwendung und Abstraktion des multidimensionalen Entscheidungsunterstützungssystems NESSI. NESSI ist eine frei zugängliche, webbasierte Software zur Simulation von nachhaltigen Energiesystemen für Gebäude und Nachbarschaften. Mithilfe eines adaptierten Design Science Forschungsansatzes, wird NESSI in dieser Dissertation in fünf aufeinander folgenden Designzyklen speziell für Akteure in Entwicklungsländern weiterentwickelt. Für jeden Designzyklus wurden Anforderungen durch systematische Marktrecherchen, Literaturanalysen, Anwendertests und Experten- und Expertinneninterviews abgeleitet. Nach umfangreichen iterativen Programmierarbeiten wird jeder Designzyklus demonstriert, evaluiert und validiert, indem die Software in verschiedenen Kontexten in Entwicklungsländern eingesetzt wird. Weitere Methoden zur Verbesserung von NESSI waren Feedback von Gutachtern sowie Präsentationen auf nationalen und internationalen Veranstaltungen. Zur weiteren Demonstration von NESSI werden in zwei Artikeln umfangreiche Fallstudien in Thailand und Kolumbien beschrieben. Durch diese Entwicklungsarbeiten entstand ein zusätzlicher Artikel in Kooperation mit einem internationalen, interkontinentalen Projektteam, in dem die Weiterentwicklung des in NESSI integrierten Lastprofilgenerator RAMP dargelegt wird. In einem weiteren Artikel wird die Funktionsweise von NESSI vorgestellt, um dessen Vertrauenswürdigkeit und Transparenz zu fördern sowie globale Anwendungsmöglichkeiten zu verdeutlichen. Der letzte Artikel befasst sich mit entstehender Designtheorie. Ausgehend von NESSIs Entwicklungsprozess, werden sieben fundierte Designprinzipien für Entscheidungsunterstützungssystemen zur Unterstützung der gesellschaftlichen Nachhaltigkeitstransformation formuliert. Während des gesamten Entwicklungsprozesses hat sich gezeigt, dass das Entscheidungsunterstützungssystem NESSI die Energiewende bottom-up unterstützt, Stakeholder informiert und Menschen befähigt. Es werden jedoch auch einige Limitationen des Tools aufgrund von Simplifikationen aufgezeigt. Darüber hinaus werden die Herausforderungen bei der Entwicklung der Software erläutert, insbesondere in Bezug auf die Definition der Stakeholder, Forschung aus der Ferne, die Komplexität und Vertrauenswürdigkeit des Tools sowie die Bedeutung von Stakeholder-Netzwerken. Akteure und Forschende werden eingeladen, NESSI weiter zu verbessern, den Ansatz zu hinterfragen und gemeinsam ein verfeinertes Modell zu entwickeln, um die Energiewende bottom-up zu fördern und die Entwicklung gesellschaftlicher Nachhaltigkeit zu unterstützen.

Schlagworte: Simulationssoftware, Entscheidungsunterstützungssystem, Design Science Research, Erneuerbare Energiesysteme, Entwicklungsländer, Designtheorie.

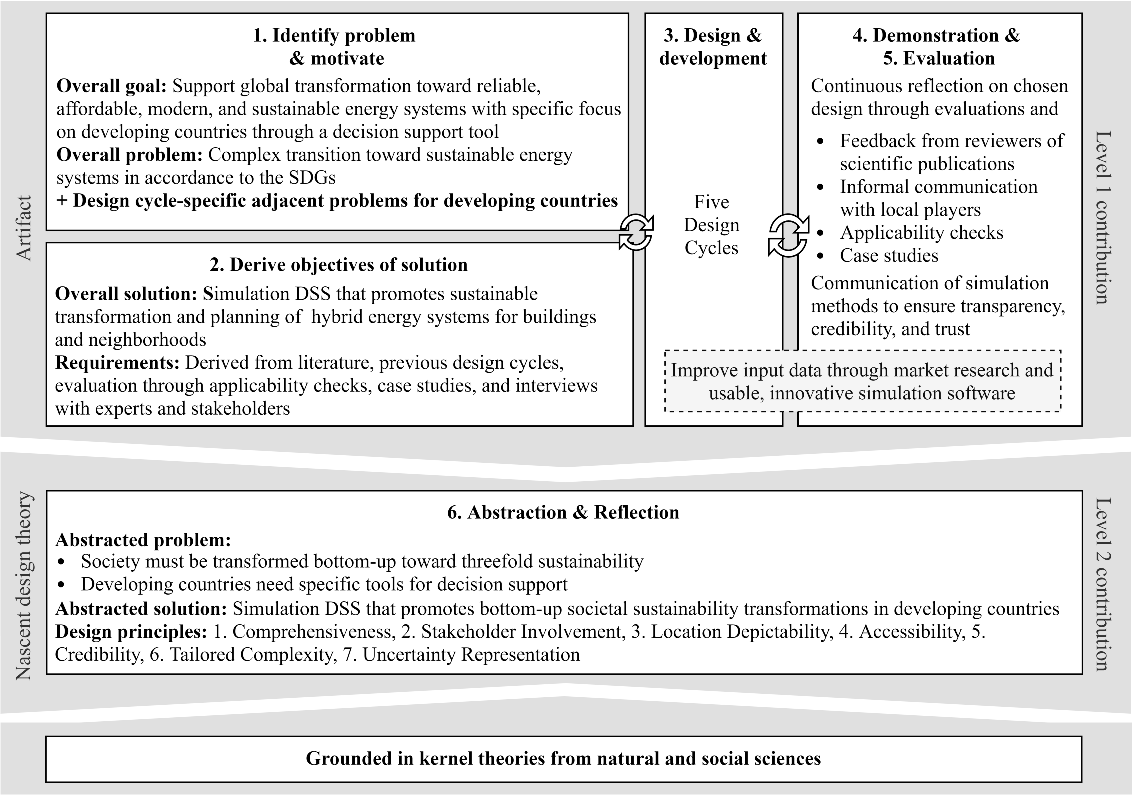
Management Summary

Recent geopolitical shifts, supply chain disruptions, and inflation have put the global energy landscape under scrutiny exposing supply dependencies, insecurities, and rising energy prices (IEA, 2022; IEA et al., 2023). Paired with climate change mitigation needs, governments worldwide have set sustainable development targets with a specific focus on energy transition in the building sector (Harish & Kumar, 2016). Decentralized renewable energy systems have proven to support these efforts by additionally strengthening the energy system's resilience, increasing its reliability, enabling supply to remote areas, and fostering independence (Al-falahi et al., 2017; IEA et al., 2023). Nevertheless, such a transition requires interdisciplinary decision-making to reconcile the often conflicting dimensions of economic viability, social acceptability, and environmental integrity (Siksnelyte et al., 2018). Traditional top-down approaches must be complemented with bottom-up actions which have proven essential for long-term successful strategies (Cherni & Kalas, 2010; Robinson & Imran, 2015). However, the intricate landscape of developing hybrid renewable energy systems poses challenges due to the complexity of energy technologies, diverse conditions on site, and various consumer needs. Economic and technological constraints, data scarcity, and inadequate policies further challenge the energy transition (Al-falahi et al., 2017; IEA et al., 2021).

The information systems (IS) community postulate that supporting the energy transition requires the integration of people, processes, software, and information technologies (Watson et al., 2010). They urge to create an ecologically sustainable society and to address climate change through the transformative power of IS. They acknowledge that information offers novel opportunities in facilitating economic and behaviorally driven solutions toward efficient energy systems (Gholami et al., 2016; Watson et al., 2010). Lehnhoff et al. (2021) recommend practical solutions over immediate theorizing specifically in relation to energy supply, access, and distribution in developing countries. In this regard, multi-criteria decision support systems (DSS) have been widely used to facilitate and support the informed decision-making process for those involved. Accordingly, numerous energy models and software tools have been developed (see, e.g., Al-falahi et al., 2017). However, a trend of excessive specificity in terms of accessibility, functionality, and structure emerged (Eckhoff et al., 2023). Tools often lack comprehensive geographical and sectoral coverage, have limited time horizons, insufficient temporal resolution, and are often specifically designed for application in developed countries (Hart et al., 2022). In addition, many tools lack 'out-of-the-box' usability (Chang et al., 2021), and Mavromatidis et al. (2019) highlight the gap between academic energy models and practical implementation.

Motivated by these calls for more solution-oriented studies that contribute to the energy transition (Lehnhoff et al., 2021), a project team at the Institute of Information Systems at Leibniz University, Hanover has been tackling this need by developing the open-access, web-based energy system simulator for buildings and neighborhoods NESSI. As part of this larger software development project, this cumulative dissertation focuses on specific characteristics of energy systems that are often found in developing countries to ensure NESSI's global applicability and to promote knowledge transfer beyond familiar circumstances. This thesis comprises of ten articles as de-

picted in Figure 1: Five publications describe five design cycles of the tool's development process, i.e., Eckhoff et al. (2022), Hart, Eckhoff, and Breitner (2023a, 2023b), Hart, Eckhoff, Schäl, and Breitner (2023), and Hart et al. (2022). The software's full functionality is then elaborated on by Eckhoff et al. (2023) to ensure credibility, trust, and transparency. Its applicability is further validated in two extensive case studies by Hart and Breitner (2022) and Redecker et al. (2023). In an additional article, the load profile simulation software RAMP is developed and described (see Lombardi et al., 2024), which has been integrated into the energy system simulator by Hart, Eckhoff, and Breitner (2023a) to improve input data. Lastly nascent design theory for the broader application class of bottom-up societal sustainability DSS in developing countries is derived by Hart et al. (2024).



1. Identify problem & motivate

Overall goal: Support global transformation toward reliable, affordable, modern, and sustainable energy systems with specific focus on developing countries through a decision support tool
Overall problem: Complex transition toward sustainable energy systems in accordance to the SDGs
+ Design cycle-specific adjacent problems for developing countries

2. Derive objectives of solution

Overall solution: Simulation DSS that promotes sustainable transformation and planning of hybrid energy systems for buildings and neighborhoods
Requirements: Derived from literature, previous design cycles, evaluation through applicability checks, case studies, and interviews with experts and stakeholders

4. Demonstration & 5. Evaluation

Continuous reflection on chosen design through evaluations and

- Feedback from reviewers of scientific publications
- Informal communication with local players
- Applicability checks
- Case studies

Communication of simulation methods to ensure transparency, credibility, and trust

Improve input data through market research and usable, innovative simulation software

6. Abstraction & Reflection

Abstracted problem:
- Society must be transformed bottom-up toward threefold sustainability
- Developing countries need specific tools for decision support

Abstracted solution: Simulation DSS that promotes bottom-up societal sustainability transformations in developing countries
Design principles: 1. Comprehensiveness, 2. Stakeholder Involvement, 3. Location Depictability, 4. Accessibility, 5. Credibility, 6. Tailored Complexity, 7. Uncertainty Representation

Grounded in kernel theories from natural and social sciences

Figure 1: Overall DSR approach adapted from Hart et al. (2024)

Following Baskerville et al. (2018), the focus is first set on the specific solution in form of an artifact before developing nascent design theory. The research agenda and each cycle follows an adapted version of Peffers et al. (2007)'s DSR approach and Gregor and Hevner (2013)'s publication scheme, i.e., (1) Identify problem & motivate, (2) Derive objectives of solution, (3) Design & development, (4) Demonstration, and (5) Evaluation. The overarching goal of the DSR journey is to support the transition toward sustainable, modern, reliable, and affordable energy systems globally (i.e., SDG 7) through a simulation based DSS. By providing a structured formalization of an energy systems various influencing factors, it is aimed that different stakeholders such as building owners, energy consultants, project planners, and policy makers are supported. They should be empowered and trained to understand the interactions and dependencies of energy technologies as well as to identify challenges and opportunities in order to make informed decisions. To avoid bias and close research gaps, the emphasis of this dissertation is put on specific circumstances in developing countries. For this purpose, the **N**ano **E**nergy **S**ystem **Si**mulator (short: NESSI) by Brauner and Kraschewski (2019) and Kraschewski et al. (2020) was tailored for stakeholders in developing countries in several design cycle.

After identifying and motivating the problem for each design cycle, the objectives of the solution were derived from literature, previous design cycles as well as stakeholder, expert, and user feedback. Specifically, three categories of challenges when developing DSS (i.e., stakeholder-oriented, model-oriented, and system-oriented) by Walling and Vaneeckhaute (2020) were used as a lens to derive the requirements in each phase. These were then translated to characteristics of the instantiations. Systematic market and literature reviews according to Watson and Webster (2020), vom Brocke et al. (2009), and Webster and Watson (2002) were further conducted to identify research gaps and needs. During this process, five problems were identified that are specifically prevalent for developing countries. From this, five design cycles emerged each focusing on a specific solution: 1) The adaptation of NESSI for conditions in developing countries, see Hart, Eckhoff, and Breitner (2023b), 2) the consideration of time variations, see Eckhoff et al. (2022), 3) the implementation as a free web application, see Hart et al. (2022), 4) the facilitation of generating load profiles, see Hart, Eckhoff, and Breitner (2023a) and Lombardi et al. (2024), and 5) the inclusion of the social dimension via a Social Sustainability Score, see Hart, Eckhoff, Schäl, and Breitner (2023). In cycle four of the development process, the load profile generator RAMP became accessible through an interface and was integrated in the energy system simulator to ensure high quality input data (Hart, Eckhoff, & Breitner, 2023a). RAMP was then further developed with an international open-source project team to produce high-resolution energy demand profiles for stakeholders in remote areas with low data availability, e.g., in developing countries (see Lombardi et al., 2024). The development process with overall DSS challenges, specific problems, requirements, and instantiations sorted by the five design cycles is summarized in Figure 2.

After extensive iterative programming works, each design cycle was demonstrated, evaluated, and validated by applying it to a suitable context in developing countries to observe its ability to address the identified problem. The applicability checks were conducted for fictive residential, commercial, and mixed buildings and neighborhoods in varying countries to highlight the tool's ability to consider local circumstances. Further methods to improve and validate NESSI included user testing (>200), reviewer feedback (20x) as well as presentation at national and international events (14x). The tool's full functionality is additionally elaborated on in Eckhoff et al. (2023) in detail to ensure trust, transparency, and credibility in the tool. Its demonstration in an urban, industrialized setting further highlights the tool's global applicability. For additional deep dives, 22 semi-structured interviews with experts from various international professional background in the energy sector and two extensive case studies in rural and urban areas of developing countries were conducted (see Eckhoff et al., 2023; Hart & Breitner, 2022; Hart et al., 2022; Redecker et al., 2023). Thus, within and between the development cycles the software and its applicability was iteratively improved by feeding back lessons learned into earlier steps. The tool is available via https://nessi.iwi.uni-hannover.de/en/.

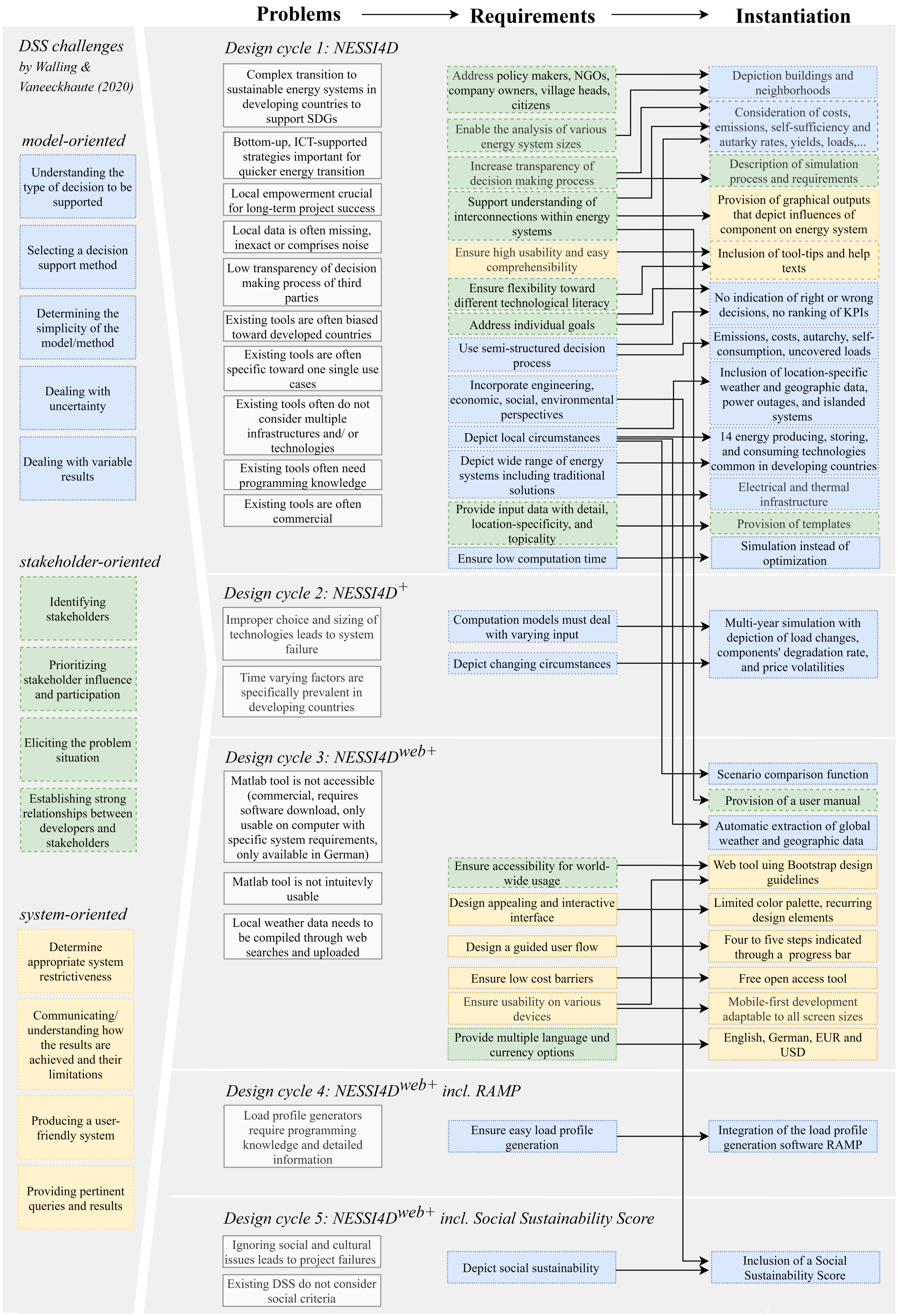


Figure 2: Problems, requirements, and instantiations of the design process adapted from Hart et al. (2024)

Various tools and skills were applied in the course of this work. Different programming languages such as MATLAB and Python as well as collaboration tools such as Gitlab and Github were used to develop the tool. The statistical software programs R and STATA were applied to analyze longitudinal household surveys for energy demand profiles. Further, the career-oriented social network LinkedIn was employed to ensure a wide reach for expert interview invitations and to promote the software. Lastly, survey tools such as LimeSurvey were used to conduct international online and on-site energy demand surveys.

After NESSI's instantiations through user tests, applicability checks, case studies, and interviews, nascent design theory for the wider application of bottom-up societal sustainability transformation, was derived by Hart et al. (2024). To this end, the authors expanded the publication scheme of Gregor and Hevner (2013) to include the sixth step Abstraction & Reflection (see Figure 1). They formalized their findings, i.e., nascent design theory, in the form of design principles through continuous reflection and learning from the feedback of users, reviewers and interviewed experts. Additionally, they derived design features that address technical specifics for each design principle. They based the formulation and presentation of the design principles on the structure of Gregor et al. (2020) and the re-usability criteria of Iivari et al. (2021). They validated the design principles and features through grounding, i.e., kernel theories from related literature as well as social and natural sciences. Specifically, they employed mechanism five by Möller et al. (2022), which uses kernel theory to transform design requirements to design principles. They categorized their research in the contribution levels of Gregor and Hevner (2013): While they consider the artifact development to be a level 1 contribution, they moved to level 2 when formulating design principles and features. The seven design principles are summarized in Table 1.

Table 1: Grounded design principles adapted from Hart et al. (2024)

Design principle	**Grounding**
Comprehensiveness: Enable a comprehensive analysis that considers the technological as well as the three sustainability dimensions.	SDGs (United Nations, 2015), Three Pillars of Sustainability (Purvis et al., 2019)
Stakeholder involvement: Identify stakeholders of the decision and ensure their participation and collaboration.	Participatory Action Research (Mumford, 1983)
Location depictability: Enable the consideration of site-specific characteristics and circumstances.	Contingency Theory (e.g., Gordon & Miller, 1976; Reinking, 2012)
Accessibility: Ensure an accessible artifact for stakeholders of various capabilities and technological constraints.	Design for All (Persson et al., 2015)
Credibility: Convey credibility through a transparent artifact model and its boundaries.	Source Credibility Concept (Giffin, 1967; Hovland et al., 1953), Transparency Theory (Wehmeier & Raaz, 2012)
Tailored complexity: Create a simple, supporting artifact that provides explicit features for advanced analyses.	Bounded Rationality & Satisficing Concept (Simon, 1979)
Uncertainty representation: Allow for the consideration of uncertain circumstances and developments.	VUCA World (e.g., Mack & Khare, 2016), DIKW Pyramid (Awad & Ghaziri, 2004)

The applicability checks, case studies as well as user and expert feedback confirmed the suitability of the developed web-based tool for its intended application, i.e., bottom-up decision support for planning hybrid energy systems globally. During demonstrations and evaluations, the tool showed robustness, practicality, and effectiveness. It met the specified stakeholder-, model-, and system-oriented requirements and strengthens the decision-making processes for a wide range of stakeholders. However, several challenges emerged of which four are pointed out specifically: First, NESSI's no-cost approach may foster skepticism and reluctance among users due to data privacy concerns. The tool's association with one research institute may not suffice for the international audience. Second, the remote research approach enabled efficiency, cost-effectiveness, and the utilization of diverse expertise. However, a development process in close collaboration with stakeholders, real-time feedback, and field testing may have addressed difficulties with data availability and quality, validated assumptions, and enhanced the tool's practical application. As the development team was solely based in Germany, the effects of this approach may be particularly pronounced in research on global applications. Third, the broad definition of stakeholders introduces complexity by requiring responsiveness to their diverse needs. Numerous features increase the time needed to complete simulations, the level of knowledge required, and may discourage certain user groups. Fourth, it was found that there is a constant trade-off between usability and level of detail. Thus, it is essential to recognize that DSS do not capture the complexities of reality. Assumptions and simplifications may distort results. It is, thus, highlighted that the DSS provides the framework to transform technical, economic, social, and environmental data into information. The user or decision maker is responsible for sourcing this information, critically analyzing its relationships, patterns and principles, identifying the underlying problem, and then making a final decision for their ideal energy system. Users are encouraged to critically evaluate and discuss NESSI's inputs and results. User supervision continues to have a significant impact on the effectiveness and efficiency of the tool. Consequently, it is essential to keep collecting user feedback and undertaking expert interviews in order to further evaluate the balance between complexity, applicability, realistic outcomes, and usability. To effectively establish a solid foundation of credibility, validity, and trust, collaboration between local academics and practitioners should be built, communication and training initiatives improved, and applicability checks on site conducted. It is further recommended to conduct an extensive test program at various locations including verification, validation, and beta-testing to ensure the tool's usability, efficacy, acceptability, and indication of limitations. As NESSI is an excellent foundation for further research, stakeholders and researchers are invited to further improve the tool, challenge the approaches, and together develop a more refined model to foster the bottom-up energy transition.

Dissertation Structure, Publication Overview, and Task Allocations

This cumulative dissertation comprises of ten research articles that were written, submitted, and mostly published in collaborative teams between 2020 and 2024. The dissertation's structure follows the overarching research agenda. Thus, the individual articles are not summarized distinctly, but for each section information from all ten articles is drawn. In some instances, articles are directly related to specific sections as indicated in Tables 2 and 3. The tables further give a comprehensive overview of each article including title, author constellation as well as the respective outlet and their metrics. Accordingly, the tables are also not structured chronologically, but corresponds to the research agenda and structure of the dissertation. Each research article, whether published, submitted or under revision, is a comprehensive *completed research article* which underlies a single- or double-blinded peer review process. Two different metrics are included: The VHB JOURQUAL 3 (VHB) systematically assigns grades (A+ to D) (German Academic Association for Business Research, 2014). Given the thematic focus of the dissertation on energy informatics and development studies, a cross-disciplinary metric is added. The SCImago Journal Rank (SJR) divides journals into quartiles (Q1 to Q4) and ranks them based on their research area (Scimago, 2023). In the following, the task allocation among the authors is described briefly.

The journal article *Tool-based Renewable Energy System Planning Using Survey Data: A Case Study in Rural Vietnam* is based on my master thesis that Michael H. Breitner and Sarah Eckhoff supervised (Hart, 2020). It describes the first design cycle of the software tool NESSI in which it was tailored to be applicable for stakeholders in developing countries. I further developed a process model to guide researchers and users through energy system analyses. I followed this process model when conducting the application check for a representative neighborhood in rural Vietnam, for which I collected market data, analyzed longitudinal household data from the Thailand Vietnam Socio-Economic Panel (TVSEP) (TVSEP, 2023) with STATA, and used the tools RAMP by Lombardi et al. (2019) and NESSI for the simulation. I wrote the first draft of the article on my own with supervision and valuable feedback of my two co-authors. During revision, Sarah Eckhoff added the research design section and revised the artifact description. The article was published in the Springer journal *Environment, Development, and Sustainability*.

Sarah Eckhoff, Michael H. Breitner, and I published the conference paper *Sustainable Energy System Planning in Developing Countries: A Decision Support System Considering Variations Over Time* in the proceedings of the *55th Hawaii International Conference on System Sciences* (Eckhoff et al., 2022). I had the idea to incorporate multi-year simulations into NESSI and developed the first prototype, thus, initiating the second design cycle. For the paper, I wrote the introduction, literature review and related research, discussion, limitations, and conclusions. Sarah Eckhoff further developed, improved, and revised the prototype, wrote the research design as well as the artifact description. We worked together on the applicability check: While I synthesized the load profile by analyzing household data and using the software RAMP as well as conducting market research for the inputs, Sarah Eckhoff conducted the calculations with NESSI and elaborated on the simulation's findings in the paper. Michael H. Breitner provided helpful feedback during discussions. Sarah Eckhoff presented our work virtually in January 2022.

The article *Accessible Decision Support for Sustainable Energy Systems in Developing Countries* by Sarah Eckhoff, Michael H. Breitner, and me was published in the Springer journal *Energy Informatics* (Hart et al., 2022). The development of NESSI's web version described in this article was a joint project of Sarah Eckhoff (project and development lead), Tim Brauner, Tobias Kraschewski, Maximilian Heumann, and me. In this article Sarah Eckhoff, Michael H. Breitner, and I presented the web tool's application in developing countries and, thus, the third design cycle. I conceptualized the paper and focused on the introduction, literature review, artifact description, demonstration, discussion, and conclusions. For the demonstration, I analyzed energy demand data to synthesize load profiles. Sarah Eckhoff focused on the related research, research design, evaluation, and limitations. For the interviews, I invited experts via multiple social media channels and email with the use of videos and personal invitation letters. I further prepared the questions for semi-structured interviews, organized the virtual meetings, and prepared the administrative work. I conducted the interviews with Sarah Eckhoff's support. Michael H. Breitner was discussant during the development and writing process.

The conference paper *Sustainable Energy System Planning in Developing Countries: Facilitating Load Profile Generation in Energy System Simulations* was published in the proceedings of the *56th Hawaii International Conference on System Sciences* (Hart, Eckhoff, & Breitner, 2023a). It was written by Sarah Eckhoff, Michael H. Breitner, and me. Based on the previously conducted interviews and user feedback, I had the idea to develop a graphical user interface for the established load profile generation software RAMP by (Lombardi et al., 2019) and integrate it into NESSI. We consider this to be the fourth design cycle. Sarah Eckhoff developed the web interface and wrote the research design and artifact description. I wrote the introduction, related research, literature review, applicability check, discussion, limitations, further research, and conclusions. For the applicability check, I analyzed household data, developed demand profiles, and synthesized the load profiles, before conducting the simulations and presenting results and findings. I presented our joint work in Hawaii, USA, in January 2023. Through this article, we connected with and joined the RAMP open-source project team.

The article *RAMP: Stochastic Simulation of User-Driven Energy Demand Time Series* was submitted by Francesco Lombardi, Pierre-François Duc, Mohammad Amin Tahavori, Claudia Sanchez Solis, Sarah Eckhoff, Francesco Sanvito, Gregory Ireland, Sergio Balderrama, Johann Kraft, Gokarna Dhungel, Sylvain Quoilin, and me. The paper was published in the *The Journal of Open Source Software*, which focuses on open-source research software (Lombardi et al., 2024). Through our usage of RAMP in previous papers as well as the development of a graphical user interface and its integration in NESSI, we joined the open-source RAMP project team comprising of faculty members and employees at TU Delft (The Netherlands), Reiner Lemoine Institute (Germany), VITO (Belgium), University of Liège (Belgium), University of Cape Town (South Africa), and Universidad Mayor de San Simon (Bolivia). We contributed to the paper by adjusting and transferring our code to RAMPs open source repository and, thus, making our work open source.

The article *Threefold Sustainable Neighborhood Energy Systems: Depicting Social Criteria in Decision Support Systems* was published in the proceedings of the *29th Americas Conference on Information Systems* (Hart, Eckhoff, Schäl, & Breitner, 2023). Based on Michael H. Breitner's and my idea, I supervised Ann-Kristin Schäl's master thesis that this paper is based on (Schäl, 2022). The article describes the fifth design cycle for which Ann-Kristin Schäl developed the first prototype and conducted interviews. I coordinated the paper and conducted a systematic literature review. Based on that, Sarah Eckhoff and I reworked the social sustainability assessment framework. Sarah Eckhoff developed its calculation and implemented the improved framework into the web version of NESSI. She wrote the research design and conducted the applicability check. Sarah Eckhoff and I jointly gathered input for the applicability check and described the design and development phases. I further wrote the introduction, related research, discussion, and conclusions. Michael H. Breitner was discussant for the paper. Sarah Eckhoff presented the paper in Panama City, Panama, in August 2023. The paper was recognized to be in the top 25 % of research articles published and received the *Best Complete Paper Award*.

The paper *Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Nano Energy System Simulation Tool NESSI* was published in the Elsevier journal *Building and Environment* and describes the development process and working of the software tool in detail (Eckhoff et al., 2023). As described above, the development was a joint project of Tim Brauner, Tobias Kraschewski, Maximilian Heumann, and me with Sarah Eckhoff as the main developer and project lead. For this paper, Sarah Eckhoff further improved the software and wrote the artifact description as well as the research design sections. Based on my previously developed semi-structured interview questionnaire, all authors invited experts. Sarah organized and mainly conducted the evaluation interviews with support of all co-authors. I wrote the introduction, literature review, and discussion. Tim Brauner wrote the first draft of the evaluation which was revised by Sarah Eckhoff. He further revised the introduction and literature review. Tobias Kraschewski contributed to the discussion. Together with Maximilian Heumann, Tobias Kraschewski provided important advice on the development of the texts and graphics. Michael H. Breitner supervised and gave valuable feedback.

The article *Fostering Energy Resilience in the Rural Thai Power System - A Case Study in Nakhon Phanom* was first presented at the *International TVSEP Conference on shocks and resilience in rural Southeast Asia* in Goettingen. At the conference I won the *Best Student Research Award* for my master thesis on which this and prior articles are based on, see e.g., Hart, Eckhoff, and Breitner (2023b). The article includes a case study situated in rural Thailand for which I analyzed household data from the TVSEP with STATA, used RAMP to synthesize load profiles, and demonstrated NESSI's applicability after its first design cycle. As the conference did not offer publication through proceedings, I reworked the article and published it in the journal *Energies* (Hart & Breitner, 2022). I worked on both articles on my own with supervision and valuable feedback from Michael H. Breitner.

The article *Fostering Sustainability with Decentral Renewable Energy for Developing Countries: A Case Study in Colombia* is based on Viktoria Redecker's bachelor thesis which I supervised (Redecker et al., 2023). It includes a case study situated in two cities in Colombia and demonstrates NESSI's applicability after its fourth design cycle. Viktoria Redecker worked on the first draft on her own which I revised before submission. For this, she conducted online surveys for stakeholders in Colombia, analyzed the data to synthesize load profiles, and simulated various energy system configurations. I reworked the paper's structure, introduction, rewrote the method section, and improved the discussion. Michael H. Breitner gave valuable feedback. The article is currently under review in the Springer journal *Energy, Sustainability and Society*.

The article *Design Principles for Decision Support Systems Promoting Societal Sustainability Transformations in Developing Countries* is currently being revised (Hart et al., 2024). This work is written jointly by Sarah Eckhoff, Michael H. Breitner, and me. I developed the idea of publishing our learnings of the whole software development process by formulating nascent design theory. I derived seven design principles and grounded them in theory. I further wrote the discussion, limitations, and further research. Sarah Eckhoff was discussant for the design principles and discussion. She further formulated the research design and methodology as well as the conclusions. We worked together on the introduction, theoretical background, and summary of the tool's development process. Michael H. Breitner was discussant and gave valuable feedback in our internal review process.

Table 2: Overview of publications and submissions (1/2)

#	Status	Title	Authors	Journal & Conference	VHB[a]	SJR[b]	Chapter	Appendix
1	Published 03/2023	Tool-based Renewable Energy System Planning Using Survey Data: A Case Study in Rural Vietnam	**Hart, M.C.G.**; Eckhoff, S.; Breitner, M.H.	Environment, Development, and Sustainability		Q1	4.2.1	A.1
2	Published 01/2022	Sustainable Energy System Planning in Developing Countries: A Decision Support System Considering Variations Over Time	**Hart, M.C.G.**; Eckhoff, S.; Breitner, M.H.	Proceedings of the 55th Hawaii International Conference on System Sciences, Virtual	C		4.2.2	A.2
3	Published 12/2022	Accessible Decision Support for Sustainable Energy Systems in Developing Countries	**Hart, M.C.G.**; Eckhoff, S.; Breitner, M.H.	Energy Informatics		Q2	4.2.3	A.3
4	Published 01/2023	Sustainable Energy System Planning in Developing Countries: Facilitating Load Profile Generation in Energy System Simulations	**Hart, M.C.G.**; Eckhoff, S.; Breitner, M.H.	Proceedings of the 56th Hawaii International Conference on System Sciences, Hawaii, USA	C		4.2.4	A.4
5	Published 06/2024	RAMP: Stochastic Simulation of User-driven Energy Demand Time Series	Lombardi, F.; Duc, P.-F.; Tahavori, M.A.; Solis, C.S.; Eckhoff, S.; **Hart, M.C.G.**; Sanvito, F.; Ireland, G.; Balderrama, S.; Kraft, J.; Dhungel, G.; Quilin, S.	The Journal of Open Source Software			4.2.4	A.5

[a] Based on German Academic Association for Business Research (2014) in VHB table *Business and Information Systems Engineering*

[b] 2022 SJR quartile based on Scimago (2023)

Table 3: Overview of publications and submissions (2/2)

#	Status	Title	Authors	Journal & Conference	VHB[a]	SJR[b]	Chapter	Appendix
6	Published 08/2023	Threefold Sustainable Neighborhood Energy Systems: Depicting Social Criteria in Decision Support Systems ***Best Complete Paper Award***	**Hart, M.C.G.**; Eckhoff, S.; Schäl, A.-K.; Breitner, M.H.	Proceedings of the 29th Americas Conference on Information Systems 2023, Panama City, Panama	D		4.2.5	A.6
7	Published 06/2023	Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Nano Energy System Simulation Tool NESSI	Eckhoff, S.; **Hart, M.C.G.**; Brauner, T.; Kraschewski, T.; Heumann, M.; Breitner, M.H.	Building and Environment		Q1	4.3	A.7
8	Published 01/2022	Fostering Energy Resilience in the Rural Thai Power System - A Case Study in Nakhon Phanom	**Hart, M.C.G.** and Breitner, M.H.	Energies		Q2	4.4.1	A.8
9	Under Review 08/2023	Fostering Sustainability with Decentral Renewable Energy for Developing Countries: A Case Study in Colombia	Redecker, V., **Hart, M.C.G.**, and Breitner, M.H.	Energy, Sustainability and Society		Q2	4.4.2	A.9
10	To be Submitted	Design Principles for Decision Support Systems Promoting Societal Sustainability Transformations in Developing Countries	**Hart, M.C.G.**; Eckhoff, S.; Breitner, M.H.				5	A.10

[a] Based on German Academic Association for Business Research (2014) in VHB table *Business and Information Systems Engineering*

[b] 2022 SJR quartile based on Scimago (2023)

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List of Abbreviations

CO_2	Carbon Dioxide
DIKW Pyramid	Data-Information-Knowledge-Wisdom Pyramid
DSR	Design Science Research
DSS	Decision Support System
FIT	Feed-In Tariff
GHG	Greenhouse Gas
GUI	Graphical User Interface
IS	Information Systems
kW	Kilowatt
kWh	Kilowatt Hour
NESSI	Nano Energy System Simulator
NESSI4D	NESSI for Developing Countries
NESSI4D^{+}	NESSI4D including multiyear calculation
NESSI4D^{web+}	NESSI4D^{+} as web application
SDGs	Sustainable Development Goals
STATA	Software for Statistics and Data Science
TVSEP	Thailand Vietnam Socio-Economic Panel
USD	United States Dollar
VUCA World	Volatility-Uncertainty-Complexity-Ambiguity World

1 Introduction

Recent geopolitical and economic shifts, exemplified by Russia's invasion into Ukraine, ongoing supply chain disruptions resulting from the Covid-19 pandemic, and soaring inflation, have put the global energy landscape under scrutiny. National energy supply insecurities were uncovered and fast rising energy prices ensued (IEA, 2022; IEA et al., 2023). Vulnerable nations are additionally confronted with dependence on external sources and challenged by increasingly electrified global economies (Al-falahi et al., 2017; UNDP, 2016). Paired with the urgent need to mitigate climate effects, governments worldwide have, therefore, set national and international targets toward societal sustainable development (see, e.g., Sustainable Development Goals (SDGs)) with a specific focus on energy transition. The integration of decentralized hybrid renewable solutions in the energy-intensive building sector supports these endeavors (Harish & Kumar, 2016). They do not only provide energy to remote regions, but also strengthen resilience, increase reliability, and facilitate environmentally conscious transitions (Al-falahi et al., 2017; IEA et al., 2023). To maximize societal impact, international energy initiatives are promoting new strategies, innovative business models, and advanced technologies which include both top-down and bottom-up approaches (Al Irsyad et al., 2017; IEA et al., 2023; Werlen et al., 2022). Granting autonomy to governments, businesses, building owners, researchers, and non-governmental organizations is essential to support the SDGs. However, the intricate landscape of developing hybrid renewable energy systems poses significant challenges due to the complexity of energy technologies, on-site conditions, and diverse consumer needs (Al-falahi et al., 2017). Economic constraints, information scarcity, and inadequate policies further challenge the energy transition, particularly in developing countries (Al-falahi et al., 2017; IEA et al., 2021). Thus, stakeholders are faced with the complex task of reconciling cost-effectiveness, energy resilience, and environmental sustainability when transitioning their energy infrastructure. Especially for less experienced stakeholders, accessible and reliable decision support is essential. The growing demand for energy consultants further underlines the need for tools that enable informed decision-making.

The information systems (IS) community postulate that supporting the energy transition requires the integration of people, processes, software, and information technologies (Watson et al., 2010). They urge to create an ecologically sustainable society, highlight the need to address climate change through transformative power of IS, and acknowledge that information offers novel opportunities in facilitating economic and behaviorally driven solutions toward efficient energy systems (Gholami et al., 2016; Watson et al., 2010). Lehnhoff et al. (2021) recommend practical solutions over immediate theorizing, particularly in relation to energy supply, access, and distribution in developing countries. Advocating strategies to reduce carbon emissions, they further highlight the role of decision support systems (DSS) in the development of sustainable energy systems. Multi-criteria DSS have been widely used to facilitate complexities of renewable energy systems (Al Irsyad et al., 2017). By providing a structured formalization of dispersed knowledge, energy system models help to understand the interactions and dependencies between components, test innovative technologies, identify challenges and opportunities, and address the growing need for scenario planning (Pfenninger et al., 2014). Accordingly, numerous energy models and software tools have been developed (see, e.g., Al-falahi et al., 2017). Yet they are often specific in terms of their accessibility, functionality, and structure. Tools often lack comprehensive geographical and sectoral coverage, have limited time horizons, insufficient temporal resolution, and are often specifically designed for developed countries (Eckhoff et al., 2023; Hart et al., 2022).

Motivated by calls for more solution-oriented studies that contribute to the energy transition (Lehnhoff et al., 2021), a project team at the Institute of Information Systems at Leibniz University, Hanover has been tackling this need by developing the open-access, web-based energy system simulator for buildings and neighborhoods NESSI. As part of this larger software development project, this cumulative dissertation focuses on specific characteristics of energy systems that are often found in developing countries to ensure NESSI's global applicability and to promote knowledge transfer beyond familiar circumstances. The research agenda comprises ten research papers and is structured following Baskerville et al. (2018)'s methodology by first developing the specific solution in form of an artifact before formulating nascent design theory. As vom Brocke et al. (2020) advocate that design science research (DSR) is a driver for a sustainable transformation of society, the DSR and publication approaches by Peffers et al. (2007) and Gregor and Hevner (2013) are adapted and NESSI's development process described through five design cycles. Throughout this process, NESSI is continuously tested and validated through user testing, expert interviews, and (inter-)national public and research events for iterative improvements. For transparency, the tool's full functionalities and calculations are elaborated on in detail. Then, the software is further demonstrated and validated with in-depth case studies. Lastly, nascent design theory for bottom-up societal sustainability transformation DSS in developing countries is derived by abstraction and reflection following Gregor et al. (2020) and Möller et al. (2022).

Accordingly, this dissertation is structured as follows: In Section 2, a broad literature and conceptual review of the relevant topics is given by extracting information from all articles comprising this dissertation. Then, the overall research design and methodology of the research agenda is presented in Section 3. In Section 4, the software development process is elaborated: First, its requirements and the five design cycles are introduced in Subsections 4.1 and 4.2 by summarizing the five software development articles by Hart, Eckhoff, and Breitner (2023b), Eckhoff et al. (2022), Hart et al. (2022), Hart, Eckhoff, and Breitner (2023a), and Hart, Eckhoff, Schäl, and Breitner (2023). This chapter also refers to the work of Lombardi et al. (2024), in which they develop and describe the load profile simulation software RAMP. Second, the specific functionality of NESSI's current version for global application based on Eckhoff et al. (2023)'s work is introduced in Section 4.3. Third, in Subsection 4.4, NESSI's ability to analyze country-specific energy problems is demonstrated with case studies, thereby, summarizing two articles by Hart and Breitner (2022) and Redecker et al. (2023). In Section 5, the development, evaluation, and application of the tool is abstracted and reflected on as described by Hart et al. (2024). Thus, generalized design principles and features as actionable guidelines for the wider application class of bottom-up societal sustainability transformation DSS in developing countries are derived to contribute to nascent design theory. Lastly, the research agenda and its comprising articles are critically discussed, limitations specified, and future research possibilities outlined in Sections 6 and 7 before concluding this work in Section 8.

2 Literature Review and Conceptual Background

2.1 Sustainable Development, Green IS, and the Role of Information Systems

Under the title *Transforming our World*, the United Nations has introduced the 17 SDGs, which aim to improve and harmonize interrelated economic, environmental, and social conditions through individual, national, and international efforts (United Nations, 2015). These goals enhance sustainable development to ensure that present needs are met without compromising the ability of future generations to meet their own needs (United Nations, 1987). Such a transformation requires interdisciplinary decision-making to reconcile the often conflicting dimensions of economic viability, social acceptability, and environmental integrity (Siksnelyte et al., 2018). Top-down methodologies tend to encounter substantial challenges on regional and local levels. They typically employ standardized solutions that neglect the necessity for culturally and regionally tailored approaches. The decision-making process and the long-term success of solutions require a complementary bottom-up approach that includes the involvement and participation of local citizens and structures to enable and motivate joint action (Werlen et al., 2022). The complexity of decision making, such as the technical requirements underlying a problem or the unique needs of a site or community, combined with incomplete information, is often a challenge. Despite these imperatives, few research papers provide empirical evidence or explicitly refer to the SDGs (Leong et al., 2020).

Thus, scholars of the IS community state that it requires the integration of people, processes, software, and information technologies to support individual, organizational, and societal sustainability goals. They consider information to be central to informed decision-making (Watson et al., 2010). IS research can and needs to address critical global challenges such as environmental degradation and climate change (Gholami et al., 2016). The IS community also highlights sustainability as a fundamental dimension (Seidel et al., 2017). Gregor et al. (2014) further state that particularly in developing countries, IS can improve economic and societal conditions. In the field of Green IS, there is a high demand for solution-oriented research that use the transformative power of IS to mitigate negative environmental impacts (Gholami et al., 2016, p. 529). Recognizing that ’energy + information > energy’, the IS community highlights the central role of information in facilitating economic and behavioral solutions for energy efficiency, and, thus, energy system design (Watson et al., 2010).

This is particularly relevant in developing countries, where energy vulnerability, dependencies, and unreliability pose great risks. Although the global energy landscape has improved in the last decade, stakeholders are still vulnerable to supply shocks, price fluctuations, and political tensions. Where energy supply is scarce, the situation is expected to worsen due to population growth and increasingly electrified economies (UNDP, 2016). Unreliable electricity supply endangers public safety, has negative impacts on operations, and is costly. It is found that the successful achievement of SDG 7, i.e., clean energy for all, evidently raises living standards, strengthens competitiveness, and drives social transformation. However, it requires context-specific policies and strategies that take into account energy demand, supply chains, and stakeholder considerations (IEA et al., 2023; UNDP, 2016). Stakeholders must be knowledgeable about the technologies’ functionality, site-specific characteristics, and consumer-specific energy demands (Al-falahi et al., 2017). Moreover, if data is available, it is often ambiguous and complex. Thus, stakeholders require support in the intricate energy system planning process.

2.2 DSS for Applications in Developing Countries

Recognizing the transformative potential of the information society, Lehnhoff et al. (2021) emphasize practical solutions over immediate theorizing, particularly in relation to energy supply, access, and distribution in developing countries. In this regard, multi-criteria DSS can facilitate the decision-making process for those involved (Cherni & Kalas, 2010). By providing a structured formalization of dispersed knowledge, energy system models help to understand the interactions and dependencies between components, test innovative technologies, identify challenges and opportunities, and address the growing need for scenario planning (Pfenninger et al., 2014). The literature and market research, software evaluations, and analyses of existing open-source models, which were conducted in the course of this work, show that existing DSS often require programming skills due to a lack of a graphical user interface (GUI), have specific system requirements or are cost-intensive. They are also often very specific in terms of their geographical or sectoral coverage and temporal resolutions. Tools designed for scenarios in developed nations may further show biased results for application in developing countries (Al Irsyad et al., 2017; Debnath & Mourshed, 2018; Gregor et al., 2014). Adapting these models to site-specific contexts is critical, as there are shortcomings in data quality, availability, and relevance. The consideration of low energy demands, socioeconomic nuances, characteristics specific for marginalized, rural areas, and supply shortages are critical of energy system planning, but often disregarded in DSS (Debnath & Mourshed, 2018). Further, the trend of excessive specificity in terms of accessibility, functionality, and structure is found. Chang et al. (2021) and Groissböck (2019) postulate that many tools lack 'out-of-the-box' usability. Although researchers have called for solution-oriented studies, Mavromatidis et al. (2019) confirm this work's findings by highlighting the gap between academic energy models and practical implementation. For this work, 19 tools are selected and each is evaluated on ten critical criteria that emerged during software development, namely, (1) sustainability dimensions, (2) region, (3) area, (4) energy infrastructure, (5) simulation entity size, (6) simulation calculation type, (7) cost for user, (8) type of access, (9) length, i.e., availability of multiyear calculations, and (10) option to create load profiles. Each criterion is subdivided into one to four sub-criteria. The results are summarized in Table 4 and highlight the above-mentioned limitations and corresponding research need.

Table 4: Related software

Tool	**Dimensions**			**Region**		**Area**		**Energy**		**Size**			**Calculation**		**Cost**		**Access**				**Length**	**LP**[a]		**Source**
	economic	environmental	social	developing	industrial	rural	urban	thermal	electric	building	neighborhood	country	optimization	ranking-based	commercial	free	no access	code	website	software download	multiyear	rural	urban	
HOMER Pro	x	x		x	x	x	x	x	x	x	x		x		x					x	x	x		link
iHoga	x	x		x	x	x	x		x	x	x		x		x				x	x	x	x		link
ONSSET	x			x		x	x		x			x	x			x		x			x			link
SURE-DSS	x	x	x	x		x			x	x	x			x			x			x		x		Cherni et al. (2007)
MicroGridsPy	x	x		x		x		x	x		x		x			x		x			x	x		link
EnergyPLAN	x	x		x	x		x	x	x			x	x			x				x				link
NESSI	x	x			x		x	x	x	x				x			x							Kraschewski et al. (2020)
RETScreen	x	x		x	x	x	x	x	x	x	x		x		x					x	x			link
Hybrid2	x	x		x		x			x	x	x			x		x				x	x	x		link
Velix		x			x		x	x	x	x				x		x	x							Loock et al. (2013)
GreenFingerprint		x			x		x	x	x	x					x		x							Ekman et al. (2015)
Ob-based DSS	x				x		x	x		x				x			x				x			Kontopoulos et al. (2016)
DAREED	x	x			x		x	x	x	x	x		x				x							Irani et al. (2015)
Model.energy	x			x	x	x	x		x		x	x	x			x			x					link
En-ROADS	x	x		x	x			x	x			x	x			x			x		x			link
Demand Analyst	x	x		x		x		x	x		x		x		x					x	x		x	link
ESCoBox		x		x		x			x	x	x			x		x				x			x	link
LEAP		x	x	x	x	x	x	x	x		x	x	x		x					x	x	x	x	link
ARISE	x	x	x	x		x		x	x		x			x			x							Al Irsyad et al. (2019)

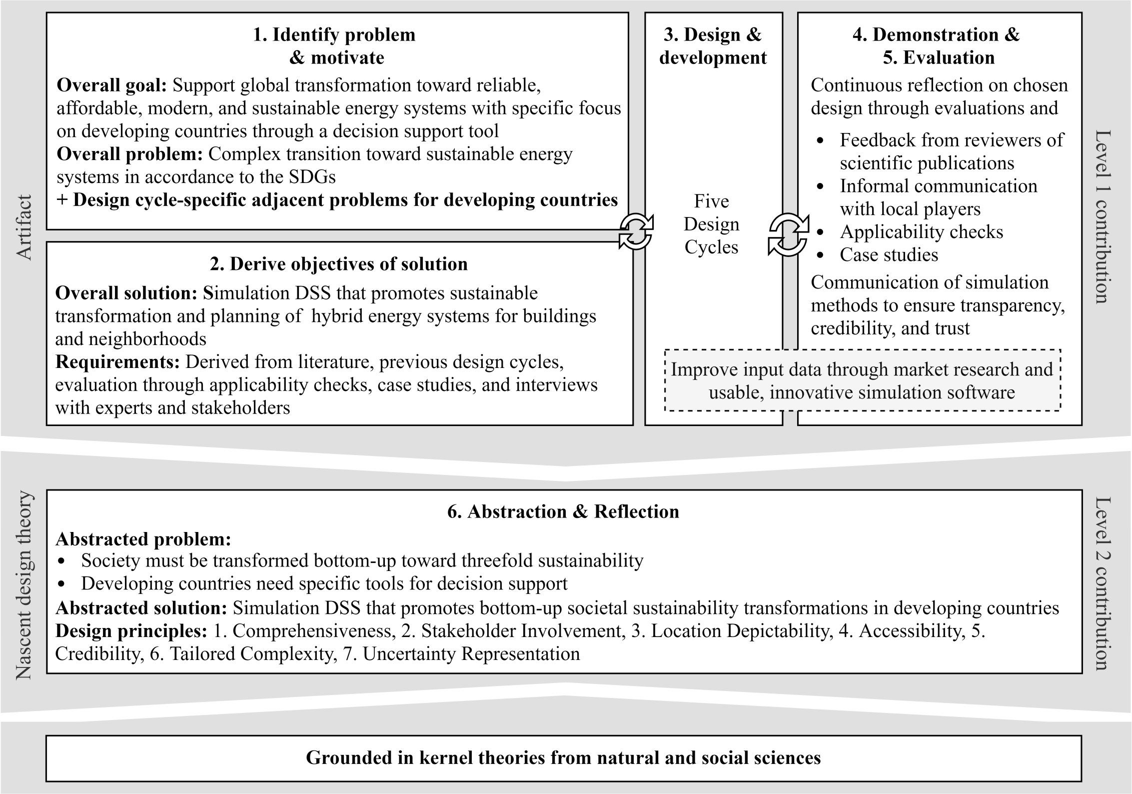
[a] Option to generate load profiles (LP = load profile)

2.3 Design Theories in Design Science Research

According to Baskerville et al. (2018), two different perspectives on the outcome of DSR projects have developed over the years. Early DSR scholars such as Peffers et al. (2007), Hevner et al. (2004), and March and Smith (1995) primarily focused on design artifacts as outcomes. Unlike Gregor and Jones (2007) who postulate that design theory can also be a product of DSR projects. As such, Fischer et al. (2010) recognize that theory can either be the basis for the creation of artifacts or as the outcome of the design process. Landwehr et al. (2022) take the former approach while Seidel et al. (2018), Cronholm and Göbel (2022), Robinson and Imran (2015), and Twomlow et al. (2022) take the latter or intertwine theorizing and artifact designing. Thus, Gregor and Hevner (2013) delineate three levels of contribution types: From less mature and concrete knowledge in form of products and processes (level 1) to a nascent design theory in the form of, e.g., design principles by abstraction (level 2) to well-developed design theories (level 3). They emphasize that all levels are valuable research contributions. Baskerville et al. (2018) state that the formulation of design theory follows on the reflection of a concrete realization and contextual evaluation of an IT artifact. This approach is adapted by many scholars for studies in developed and developing countries, e.g., Greve et al. (2020), Widjaja and Gregory (2020), Avdiji et al. (2020), Miah et al. (2020), Gregor et al. (2014), and Braa et al. (2023). The grounding of design principles in kernel theories, i.e., theories from natural or social science, has proven a positive influence in the development of design principles in regards to derivation, justification, and transformation (Möller et al., 2022; Walls et al., 1992).

3 Research Design and Methodology

According to Lehnhoff et al. (2021) IS research does not have to lead to immediate theorizing. Thus, this dissertation is solution oriented. The research agenda follows Baskerville et al. (2018)'s DSR approach by first focusing on the specific solution in form of an artifact before developing nascent design theory. By providing a structured formalization of an energy systems various influencing factors, it is aimed that different stakeholders such as building owners, energy consultants, project planners, and policy makers are supported. They should be empowered and trained to understand the interactions and dependencies of energy technologies as well as to identify challenges and opportunities in order to make informed decisions. To avoid bias and close research gaps, the emphasis of this dissertation is put on specific circumstances in developing countries. For this purpose, the **N**ano **E**nergy **S**ystem **Si**mulator (short: NESSI) by Brauner and Kraschewski (2019) and Kraschewski et al. (2020) was tailored for stakeholders in developing countries. The research approach is summarized in Figure 3.



1. Identify problem & motivate

Overall goal: Support global transformation toward reliable, affordable, modern, and sustainable energy systems with specific focus on developing countries through a decision support tool

Overall problem: Complex transition toward sustainable energy systems in accordance to the SDGs

+ Design cycle-specific adjacent problems for developing countries

2. Derive objectives of solution

Overall solution: Simulation DSS that promotes sustainable transformation and planning of hybrid energy systems for buildings and neighborhoods

Requirements: Derived from literature, previous design cycles, evaluation through applicability checks, case studies, and interviews with experts and stakeholders

3. Design & development

Five Design Cycles

4. Demonstration & 5. Evaluation

Continuous reflection on chosen design through evaluations and

- Feedback from reviewers of scientific publications
- Informal communication with local players
- Applicability checks
- Case studies

Communication of simulation methods to ensure transparency, credibility, and trust

Improve input data through market research and usable, innovative simulation software

6. Abstraction & Reflection

Abstracted problem:

- Society must be transformed bottom-up toward threefold sustainability
- Developing countries need specific tools for decision support

Abstracted solution: Simulation DSS that promotes bottom-up societal sustainability transformations in developing countries

Design principles: 1. Comprehensiveness, 2. Stakeholder Involvement, 3. Location Depictability, 4. Accessibility, 5. Credibility, 6. Tailored Complexity, 7. Uncertainty Representation

Grounded in kernel theories from natural and social sciences

Figure 3: Overall DSR approach adapted from Hart et al. (2024)

The research agenda and each cycle follows an adapted version of Peffers et al. (2007)'s DSR approach and Gregor and Hevner (2013)'s publication scheme, i.e., (1) Identify problem & motivate, (2) Derive objectives of solution, (3) Design & development, (4) Demonstration, and (5) Evaluation. After identifying and motivating the overall problem as outlined in the introduction of this work, specific challenges and objectives were derived from literature, previous design cycles as well as stakeholder, expert, and user feedback for each cycle. Specifically, the challenges when developing environmental DSS by Walling and Vaneeckhaute (2020) were used as a lens to derive the requirements in each phase. The requirements were then translated to characteristics of the instantiation. Further thorough and systematic market and literature reviews according to Watson and Webster (2020), vom Brocke et al. (2009), and Webster and Watson (2002) were conducted in these articles to identify research gaps and needs. This research led to further development of NESSI through five design cycles based on Eckhoff et al. (2022), Hart, Eckhoff, and Breitner (2023a, 2023b), Hart, Eckhoff, Schäl, and Breitner (2023), and Hart et al. (2022). After extensive iterative programming works, each design cycle was demonstrated, evaluated, and validated by applying it to a suitable context in developing countries to observe its ability of addressing the identified problem. The applicability checks were conducted for commercial buildings and fictive neighborhoods in varying countries showcasing the tool's ability to consider local circumstances globally. Further methods to improve and validate NESSI included user testing (>200x), reviewer feedback (>20x), as well as presentation with subsequent discussions at national and international events (14x). For additional deep dives, 22 semi-structured interviews with experts from various international professional background in the energy sector and two extensive case studies in rural and urban areas of developing countries, i.e., Colombia and Thailand, were conducted by Eckhoff et al. (2023), Hart and Breitner (2022), Hart et al. (2022), and Redecker et al. (2023). Thus, within and between the five design cycles the software was iteratively improved by feeding back lessons learned into earlier steps. To increase trust, transparency, and credibility the full functionality of NESSI was outlined by Eckhoff et al. (2023). Its demonstration in an urban, industrialized setting further highlights NESSI's global applicability.

A prerequisite to obtain appropriate results, is feeding in suitable input data. Thus, during NESSI's development process, the load profile generator RAMP was made accessible through an interface and was integrated in the energy system simulator to ensure high quality input data (Hart, Eckhoff, & Breitner, 2023a). RAMP was then further developed with a cross-institutional, intercontinental open-source project team to produce high-resolution energy demand profiles for stakeholders in remote areas with low data availability, e.g., in developing countries (see Lombardi et al., 2024).

A wide range of tools were used in the course of this dissertation: The development of NESSI as well as the operation of available software (e.g., RAMP) required the use of various programming languages, including MATLAB and Python as well as collaboration tools such as Gitlab and Github. The statistical software R and STATA were employed to analyze longitudinal household surveys and derive energy demand profiles. The professional social network LinkedIn was used to ensure a wide reach for expert interview invitations and promote the tool globally, and survey tools such as LimeSurvey were incorporated to conduct international energy demand surveys virtually and in the field.

After NESSI's instantiations through applicability checks, case studies, and interviews, nascent design theory in form of generalized design principles and features were abstracted for the wider application of bottom-up societal sustainability transformation by Hart et al. (2024). For this the sixth step, (6) Abstraction & Reflection, was added to Gregor and Hevner (2013)'s DSR approach. In this step, learnings from continuous reflection through feedback from users, reviewers, and expert interviewees were formalized in the form of design principles and, thus, nascent design theory derived. Additionally, design features were derived that address technical specifics for every design principle. The formulation and presentation of the design principles was oriented on the structure of Gregor et al. (2020) and the re-usability criteria of Iivari et al. (2021). The design principles and features were validated through grounding, i.e., kernel theories from related literature as well as social and natural sciences. Specifically, Möller et al. (2022)'s fifth mechanism was used which takes kernel theory to transform design requirements to design principles. Hart et al. (2024) categorized the research in the contribution levels of Gregor and Hevner (2013): While the artifact development is considered to be level 1, level 2 is reached when formulating design principles and features.

4 Artifact Design and Development Process

The overarching goal of the DSR journey is to support the transition toward affordable, reliable, sustainable, and modern energy globally (SDG 7) through a simulation based DSS. By providing a structured formalization of the various influencing factors of an energy system, various stakeholders such as building owners, energy consultants, project planners, and policy makers should be supported. They should be empowered and trained to understand the interactions and dependencies of energy technologies as well as to identify challenges and opportunities in order to make informed decisions. To avoid bias and close research gaps, the focus of this dissertation is put on specific circumstances in developing countries.

4.1 Challenges, Requirements, and Instantiations

To establish a systematic approach for the artifact design and programming process, the software development was guided by Walling and Vaneeckhaute (2020)'s categorization into the interrelated stakeholder-oriented, model-oriented, and system-oriented challenges. Enriched by literature and market research, these challenges were translated into specific software requirements. Initiated by user testing (>200), expert interviews (22x), peer reviews (20x), and (inter-)national presentations (14x), these requirements were cyclically adapted, improved, and added to.

The first category concerned the challenge of eliciting the problem situation, identifying stakeholders, prioritizing their influence and participation, and establishing strong relationships between developers and stakeholders (Walling & Vaneeckhaute, 2020). The overall aim is to support access to reliable, cost-effective, and sustainable energy systems for all, i.e., SDG 7, empower and educate local stakeholders, and enable informed decision-making. As energy system planning is complex and requires understanding and consideration of interrelated social, economic, technical, and environmental factors, the software must provide decision support (Al Irsyad et al., 2017). Paired with the overall goal of empowering and educating local stakeholders and providing bottom-up strategies, the requirement to address policy makers, non-governmental organizations, energy consultants, company, and building owners was derived (see Eckhoff et al., 2023; Hart, Eckhoff, & Breitner, 2023b; Hart et al., 2022). Hart et al. (2022) found that experts from developing countries underline the importance of showcasing energy-saving opportunities, providing educational tools as well as enabling and empowering people toward the usage of renewable energy technologies. This followed the need to be able to address individual goals globally and the provision of detailed, location-specific, and topical input data. Experts further stated the need of being able to simulate various energy system sizes (Hart et al., 2022). They pointed out that the tool must support transparency in the decision process of energy system projects as well as its calculations (Hart et al., 2022). Considering the research's focus on stakeholders in developing countries with less materially advantaged members, a high level of accessibility must be provided. Experts with professional background in developing countries specifically indicated to ensure flexibility toward different technological literacy as well as the provision of multiple language and currency options (Hart et al., 2022). Overall, close collaboration with potential stakeholders must be ensured throughout the whole development process (Werlen et al., 2022). Walling and Vaneeckhaute (2020)'s model-oriented challenges concern understanding the type of decision to be supported, selecting a decision support method, determining the simplicity of the model or method, and dealing with uncertainty and variable results. The complex decision-making process was classified as semi-structured, meaning that although the decision solution is based exclusively on the decision-maker's subjective preferences, the decision formulation can be specified and structured (Walling & Vaneeckhaute, 2020). A simulation model allows to facilitate the creation of different energy system scenarios and allow varying inputs. Underlined by Al Irsyad et al. (2017), the four sustainability dimensions economy, society, engineering, and environment must be depicted. Urmee and Md (2016) and Al-falahi et al. (2017) particularly highlight the importance of the social dimension in energy system planning for its long-term success, which is further confirmed in the extensive literature review by Hart, Eckhoff, Schäl, and Breitner (2023). Local, varying circumstances (e.g., weather and environmental conditions or individual energy demands) as well as a wide range of renewable and conventional energy-producing, consuming, and storing technologies of both, the thermal and electrical infrastructure, must be depictable. Changing circumstances and dynamic transitions must be accounted for as it influences the long-term success of energy systems (Al Irsyad et al., 2017). For developing countries, this is particularly important in regard to load demand changes, degradation, and prices (Fioriti et al., 2021; IRENA, 2020). Interviewed experts stated that particularly in rural areas, load profiles may not be readily available and urged to implement a load profile generator into the tool (Hart et al., 2022). This was confirmed through several reviews in the course of this work. Lastly, the design process must always balance the tool's complexity versus usability (Eckhoff et al., 2023; Hart et al., 2022). System-oriented challenges include the determination of appropriate system restrictiveness, communication of calculation process and its limitations, production of a user-friendly system, and provision of pertinent queries and results (Walling & Vaneeckhaute, 2020). These translated into the requirements of ensuring high usability and easy comprehensibility of the user interface with explanations of inputs, calculation, and results. These requirements were confirmed by all interviewed experts who highlighted specifically the different literacy levels of stakeholders (Eckhoff et al., 2023; Hart et al., 2022). The design must be appealing, and the user must be guided through the tool. Experts and users further stated the need of a fast tool with low computational times (Eckhoff et al., 2023; Hart et al., 2022). The tool must be usable on various devices and its usage must have low cost barriers. Interviews revealed the tool's need of conveying credibility, trust, and transparency (Hart et al., 2022). In order to ensure collaboration and communication between users and stakeholders, the authors also identified the need to share scenarios and results (Hart et al., 2022).

From these requirements, five problems specifically relevant for the case in developing countries were identified. This initiated five design cycles each focusing on one specific solution: 1) The adaptation of NESSI for conditions in developing countries (see Hart, Eckhoff, & Breitner, 2023b and Section 4.2.1), 2) the consideration of time variations (see Eckhoff et al., 2022 and Section 4.2.2), 3) the implementation as a free web application (see Hart et al., 2022 and Section 4.2.3), 4) the facilitation of generating load profiles (see Hart, Eckhoff, & Breitner, 2023a; Lombardi et al., 2024 and Section 4.2.4), and 5) the inclusion of the social dimension (see Hart, Eckhoff, Schäl, & Breitner, 2023 and Section 4.2.5). During each design cycle, several requirements were additionally met through specific solutions as depicted in Figure 4. Each design cycle was evaluated and the importance of the changes demonstrated with respective applicability checks and user testing in suitable contexts, i.e., Vietnam (Hart, Eckhoff, & Breitner, 2023b), Nepal (Eckhoff et al., 2022), Madagascar (Hart, Eckhoff, Schäl, & Breitner, 2023; Hart et al., 2022), and Sri Lanka (Hart, Eckhoff, & Breitner, 2023a). Two additional, extensive case studies were conducted for Thailand (Hart & Breitner, 2022) and Colombia (Redecker et al., 2023). The problems, challenges, requirements, and instantiations sorted by the five design cycles are summarized in Figure 4 and elaborated on in the following sub-chapters. For ease of understanding, the software is referred to as NESSI throughout this dissertation and the specific version names are only used when it is critical for context.

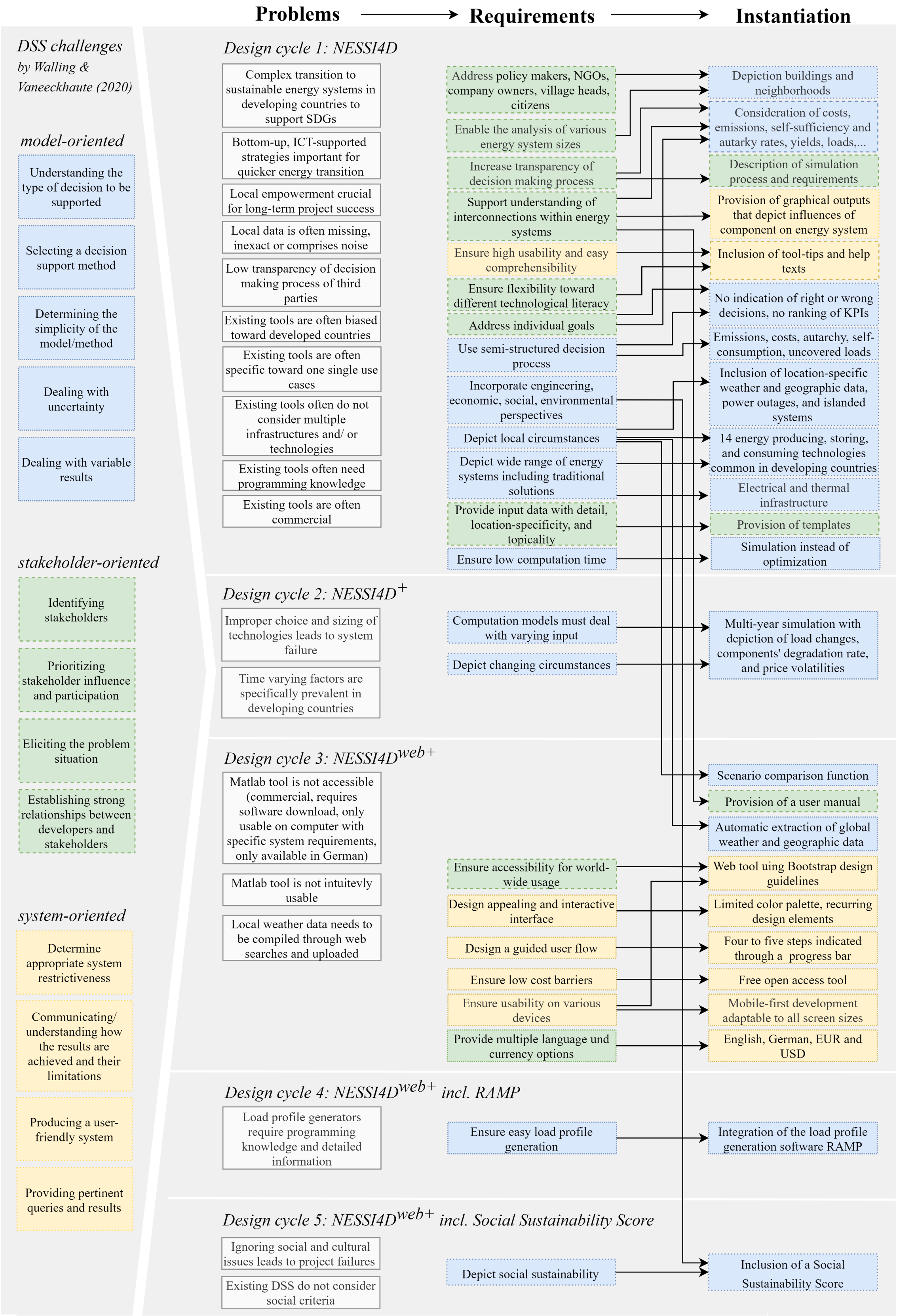


Figure 4: Problems, requirements, and instantiations of the design process adapted from Hart et al. (2024)

4.2 The Five Design Cycles

The development of NESSI started in 2018 by Brauner and Kraschewski (2019) and Kraschewski et al. (2020). They developed the first prototype as a MATLAB-based software for the use of building simulations in Germany. Based on the energy management's ranking method, NESSI calculates the thermal and electrical infrastructure, cost, and GHG emissions in hourly time steps over one year. The user is able to choose between nine technologies, i.e., heat pump, hot water storage, solar thermal and photovoltaic system, gas boiler, battery storage, combined heat and power plants as well as combustion engine or electric cars. Weather and location data was manually uploaded to calculate yields based on technological inputs such as capacities and efficiency rates. Information on the building's size and insulation as well as air temperature is used to calculate space heating. Various inputs such as feed-in tariffs, fuel prices, investment as well as operation and management cost are included to evaluate the economic impacts of the simulated energy system and GHG emission factors to analyze environmental factors.

4.2.1 Design Cycle 1: NESSI for Developing Countries

The first design cycle is elaborated on in the paper *Tool-based Renewable Energy System Planning Using Survey Data: A Case Study in Rural Vietnam* by Hart, Eckhoff, and Breitner (2023b). The authors found that stakeholders globally need to be informed about the technological capabilities of renewable energies as well as their economic, ecological, and social impacts to be empowered to build long-term sustainable energy systems. However, complexities of energy technologies, on-site geographic and weather conditions, consumer-specific energy demands, social and cultural needs, data scarcity, and lack of related studies complicate the development process and formulation of supporting, evidence-based policies, specifically in developing countries (Al-falahi et al., 2017; IEA et al., 2021; Urmee & Md, 2016). Local stakeholders must be empowered to partake in the planning of hybrid energy systems (UNDP, 2016; Werlen et al., 2022). Existing multi-energy DSS have proven valuable in this regard, but are often commercial, require knowledge of programming languages or are not suited for specific circumstances mainly found in developing countries (Hart, Eckhoff, & Breitner, 2023b) (see Subsection 2.2). Therefore, in the first design cycle NESSI for developing countries (short: NESSI4D) was developed following Peffers et al. (2007) and Gregor and Hevner (2013) as depicted in Figure 5.

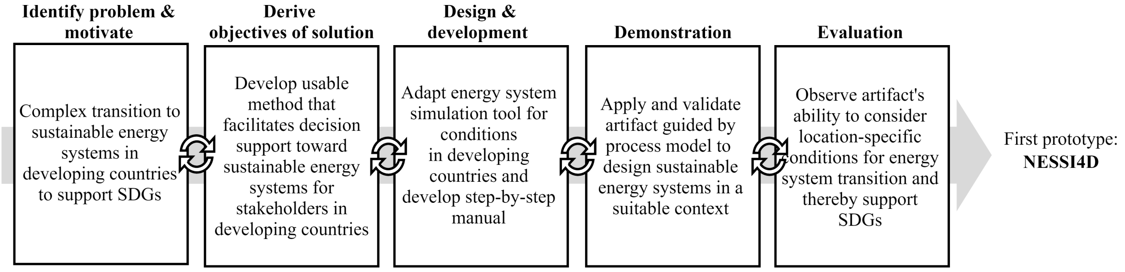
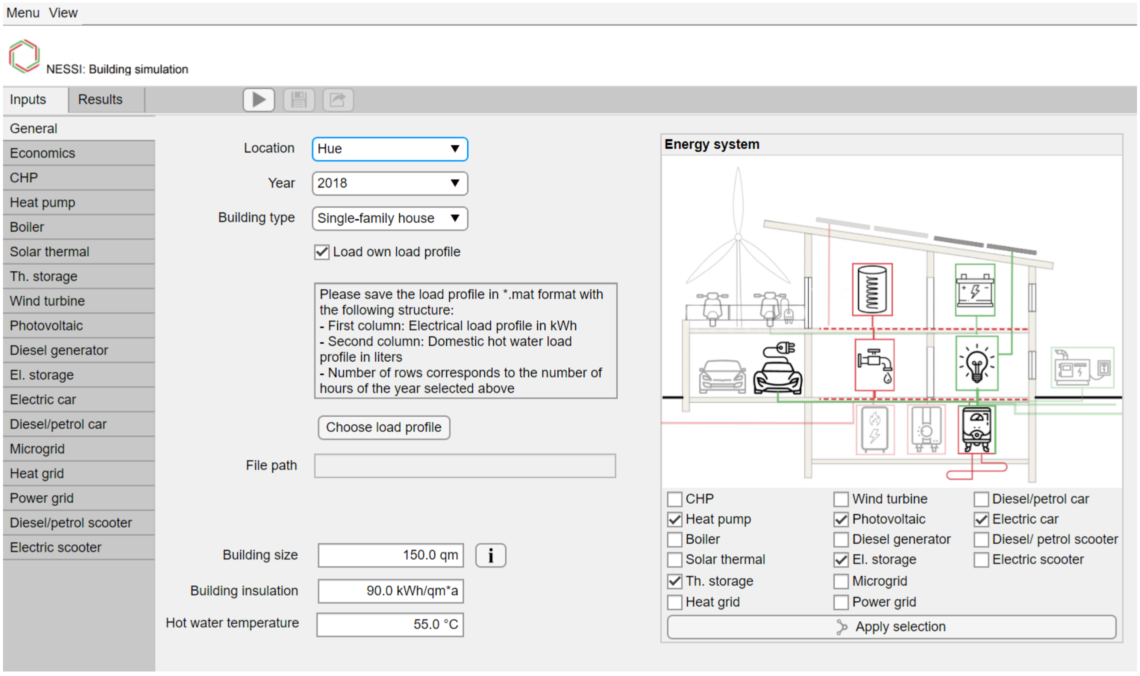


Figure 5: DSR cycle 1 toward NESSI4D adapted from Hart, Eckhoff, and Breitner (2023b)

For the use in developing countries, the electric infrastructure was extended by a small-scale wind turbine, diesel generator as well as electric and fuel-powered motorcycles. The power grid model was modified to enable the simulation of power outages, off-grid applications, and reactive loads. Users were further enabled to combine building simulations to analyze neighborhoods. Additionally, the currency United States Dollar (USD), various types of pre-defined load profiles (country-, building-, and household-specific), and weather data from three locations in developing countries (Nakhon Phanom, Thailand; Thua Thien-Hue, Vietnam; Ambovombe, Madagascar) were added to the software's library. For the latter, the authors analyzed longitudinal household data from the Thailand Vietnam Socio Economic Panel (TVSEP) and Enclude (Enclude BV, 2018; TVSEP, 2023). The software was also branded with a logo. The resulting GUIs of the building simulation are shown in Figures 6 and 7.



Location: Hue
Year: 2018
Building type: Single-family house
☑ Load own load profile

Please save the load profile in *.mat format with the following structure:
- First column: Electrical load profile in kWh
- Second column: Domestic hot water load profile in liters
- Number of rows corresponds to the number of hours of the year selected above

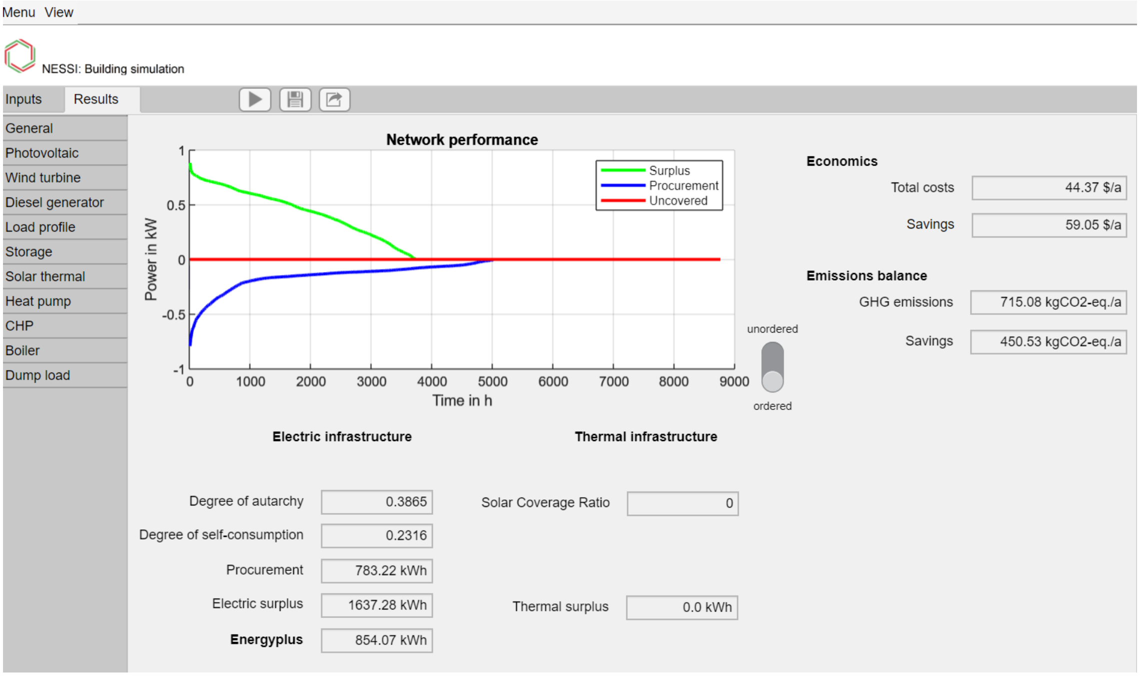
File path:

Building size: 150.0 qm
Building insulation: 90.0 kWh/qm*a
Hot water temperature: 55.0 °C

☐ CHP
☑ Heat pump
☐ Boiler
☐ Solar thermal
☑ Th. storage
☐ Heat grid
☐ Wind turbine
☑ Photovoltaic
☐ Diesel generator
☑ El. storage
☐ Microgrid
☐ Power grid
☐ Diesel/petrol car
☑ Electric car
☐ Diesel/ petrol scooter
☐ Electric scooter

Figure 6: NESSI4D's GUI depicting the Inputs tab by Hart, Eckhoff, and Breitner (2023b)

Following the process model for planning energy systems by Hart, Eckhoff, and Breitner (2023b), the authors conducted an applicability check for a representative village in Vietnam. Step 1), i.e., assess the country's situation, stakeholders' goals, and international literature, revealed that the rapidly increasing electricity demand can be met with the abundance of renewable energy opportunities. Because common supplies are fossil fuel intensive or considered exploited, the government set strict renewable energy targets (Nong et al., 2020). The authors found that related studies have analyzed the countrys overall energy situation, consumption behavior, renewable resource potentials, implementation challenges, and policies. However, while several works have simulated the option of large-scale renewable energy projects, decentralized solutions particularly in rural settings have scarcely been evaluated (Hart, Eckhoff, & Breitner, 2023b). As these studies often use inexact or outdated load and weather data, do not simulate hybrid options, and disregard environmental impacts, the need for further research was prevalent.



Economics

Total costs 44.37 $/a

Savings 59.05 $/a

Emissions balance

GHG emissions 715.08 kgCO2-eq./a

Savings 450.53 kgCO2-eq./a

Electric infrastructure

Degree of autarchy 0.3865

Degree of self-consumption 0.2316

Procurement 783.22 kWh

Electric surplus 1637.28 kWh

Energyplus 854.07 kWh

Thermal infrastructure

Solar Coverage Ratio 0

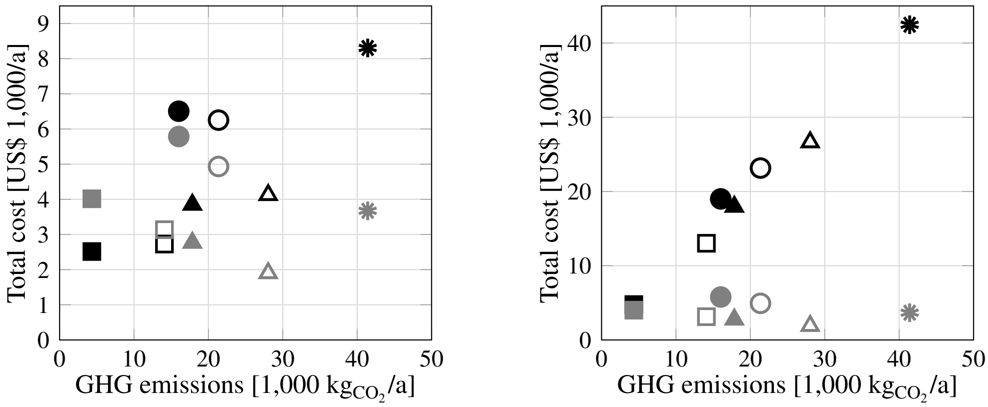
Thermal surplus 0.0 kWh

Figure 7: NESSI4D's GUI depicting the Results tab by Hart, Eckhoff, and Breitner (2023b)

In Step 2), i.e., evaluate energy demand and synthesize load profiles, the challenge of missing data was circumvented by evaluating household data with the software STATA and generating electricity demand profiles using information from the TVSEP (TVSEP, 2023). This demand profile was then fed to the load profile generation software RAMP by Lombardi et al. (2019). RAMP is a software tool for the stochastic simulation of user-driven multi-energy demand time series based on simple data such as surveys. The tool is specifically designed to create high-resolution load profiles by applying a high degree of stochasticity to multiple parameters related to appliance characteristics and consumer usage behavior, such as number of appliances, power consumption, and frequency, duration, and time windows of use (Lombardi et al., 2019). The software is considered one of the most comprehensive and functional tools in terms of flexibility and customization (Herraiz-Cañete et al., 2022).

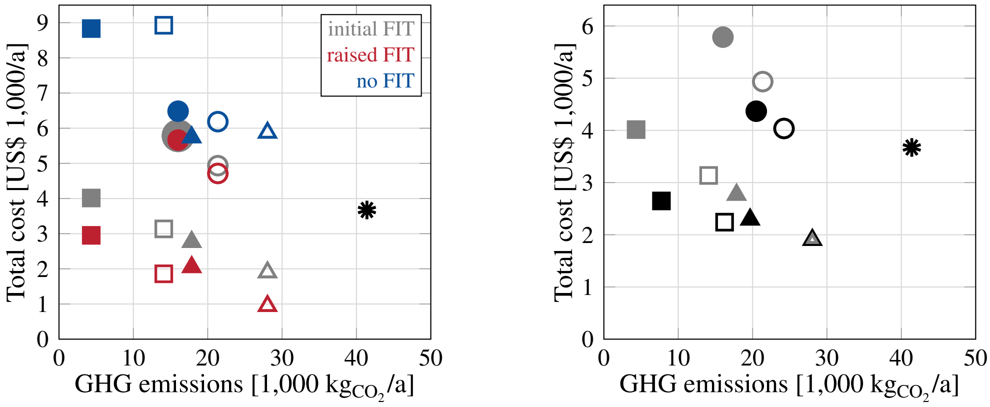
In Steps 3) and 4) geographic and weather data as well as common technologies, their prices, and settings were compiled through literature and market research. For the analyses, the authors computed different renewable energy systems consisting of variations of small-scale wind turbines, photovoltaic systems, and battery storage to the existing grid. Additionally, the authors conducted sensitivity analyses including price developments, feed-in tariffs (FIT), and investment reductions through locally producible wind turbines and second-life batteries.

The results as shown in Figure 8 depict that the current FIT structure leads to ecologically and economically advantageous renewable energy systems. Self-generated electricity reduces electricity cost, generates income through selling surplus energy, and decreases indirect GHG emissions from the grid. Photovoltaic systems are generally more appropriate due to low wind speeds at hub height of the small-scale wind turbines. With the current price developments and governmental actions of meeting increased demand with fossil fuel imports and coal mining, these advantages are expected to rise. Using locally producible technologies provides the potential of local business opportunities to foster knowledge transfer. In light of the urgency to increase electricity supply as energy demand is rising, the modular nature of such renewable energy systems may be additionally advantageous to achieve quick small-scale solutions. Feeding in electricity is beneficial to relieve stress from the grid but may also lead to grid overloads at peak times. Alternatively, surplus energy could be used to supply new electricity consuming technologies such as electric vehicles. The authors recommend energy policies and subsidies, which offer financial and technical support, because such technologies require high investment (Hart, Eckhoff, & Breitner, 2023b).



(a) Predicted prices for 2030

(b) Predicted prices for 2050



(c) Variation of FIT values

(d) Reduction of investments

✱	Grid	*gray*	Initial Results
○	Grid + Wind Turbine	*colored*	Sensitivity Results
△	Grid + Photovoltaic System	*filled*	+ Battery Storage
□	Grid + Photovoltaic System + Wind Turbine		

Figure 8: Economic and ecological impacts on the energy systems by Hart, Eckhoff, and Breitner (2023b)

In the scope of this demonstration, it was shown that NESSI4D is suitable for decision-makers that aim to design renewable energy systems in developing countries. The addition of a diesel generator uncovered electric loads as well as the neighborhood simulation were particularly important to reflect conditions on site. The authors highlight that NESSI4D further supports the user with extensive libraries which are specific for developing countries, additional help texts, automatic warnings, and various key parameters and graphs. As called for by the IS community and Leong et al. (2020), the authors state that the tool enables research in developing countries on SDG 7, SDG 1 (end poverty), SDG 13 (climate protection), SDG 11 (sustainable cities), and SDG 3 (good health and well-being) through considerations of economic and environmental factors of renewable and traditional technologies. The tool's flexibility of the various input parameters has the potential to empower local individuals, village heads, and policymakers to reflect their specific cases, understand the interrelated impacts, and make informed decisions regarding site- and target-specific energy system designs or policies (Hart, Eckhoff, & Breitner, 2023b). Nevertheless, the authors emphasized several limitations, such as biases due to assumptions, omitted factors (e.g., life cycle emissions, degradation) and changing conditions (e.g., demand and price changes). They also highlighted the potential of thermal infrastructure and electric vehicles in energy system analyses. Further, they criticized the limited consideration of social factors and the cost-intensive use of the tool given that it is a computer-based MATLAB application.

4.2.2 Design Cycle 2: Considering Time Variations

In the paper *Sustainable Energy System Planning in Developing Countries: A Decision Support System Considering Variations Over Time* by Eckhoff et al. (2022), the second design cycle is described which tackles the objective of considering time variations. The long-term sustainability of energy systems is highly influenced by time varying factors. Load demand changes are particularly prevalent in developing countries as well as areas with no prior electricity access (Fioriti et al., 2021). Improved supply chains to and from developing countries, increased demand for renewable energy technologies, and diminishing demand for as well as availability of fossil fuels influence competition and prices (IRENA, 2020). Lastly, the components' degradation rates through wear and tear affect the performance of an energy system. These uncertainties may lead to improper component sizing which has negative impact on environmental factors, reliability, and cost (Fioriti et al., 2021). Existing simulation tools allow to insert randomness and variability in average or extended load profiles, time variations, changes in percent per year of load demand, component degradation, and prices. However, these approaches are either unsuitable for contexts in developing countries, require extensive (programming) knowledge, are not tested, or are incorporated in tools that are of commercial nature (Eckhoff et al., 2022). Thus, the authors found no energy simulation DSS for developing countries that consider time variations satisfactory to their needs, motivating the adaptation of the tool toward NESSI4D^{+} following Figure 9.

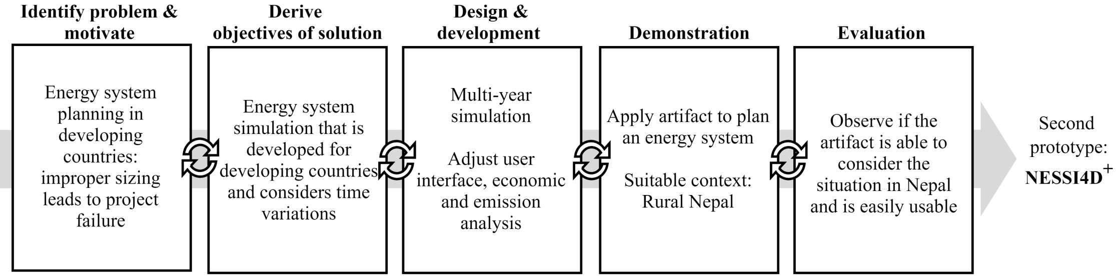
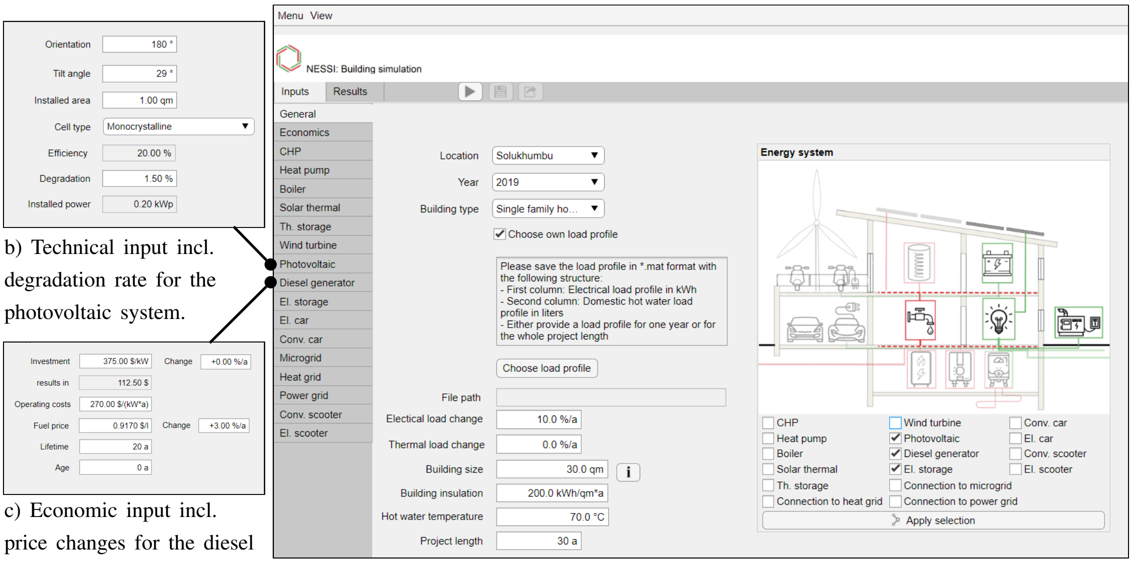


Figure 9: DSR cycle 2 toward NESSI4D$^+$ adapted from Eckhoff et al. (2022)

The authors adapted the tool to account for multiple temporal variations: First, to consider electric and thermal demand variations, the authors included annual demand changes in percent and provide the opportunity to use own multi-year load profiles. Second, they incorporated an annual degradation rate of the components capacity in percent accounting for the components' age and replacement. Third, the model was adapted by changing the simulation of solely one year in hourly time steps to the option to repeat this procedure over the project length for a multi-year simulation. These changes led to the inclusion of key indicators now depicting average results (i.e., average emissions, degree of self-sufficiency, and self-consumption) and corresponding graphs for visualization. See Figure 10 for an illustrative example of the changed GUI.



Orientation 180 °
Tilt angle 29 °
Installed area 1.00 qm
Cell type Monocrystalline
Efficiency 20.00 %
Degradation 1.50 %
Installed power 0.20 kWp

b) Technical input incl. degradation rate for the photovoltaic system.

Investment 375.00 $/kW Change +0.00 %/a
results in 112.50 $
Operating costs 270.00 $/(kW*a)
Fuel price 0.9170 $/l Change +3.00 %/a
Lifetime 20 a
Age 0 a

c) Economic input incl. price changes for the diesel generator.

Location Solukhumbu
Year 2019
Building type Single family ho...
☑ Choose own load profile

Please save the load profile in *.mat format with the following structure:
- First column: Electrical load profile in kWh
- Second column: Domestic hot water load profile in liters
- Either provide a load profile for one year or for the whole project length

File path
Electical load change 10.0 %/a
Thermal load change 0.0 %/a
Building size 30.0 qm
Building insulation 200.0 kWh/qm*a
Hot water temperature 70.0 °C
Project length 30 a

☐ CHP
☐ Heat pump
☐ Boiler
☐ Solar thermal
☐ Th. storage
☐ Connection to heat grid
☐ Wind turbine
☑ Photovoltaic
☑ Diesel generator
☑ El. storage
☐ Connection to microgrid
☐ Connection to power grid
☐ Conv. car
☐ El. car
☐ Conv. scooter
☐ El. scooter

a) Start page incl. load profile upload and load changes fields.

Figure 10: NESSI4D$^+$'s GUI including time variations by Eckhoff et al. (2022)

To demonstrate and validate the refined tool, an applicability check was conducted with a representative rural village in Solukhumbu, Nepal. The authors found that even though the electricity rate has considerably increased in the past decade, the Nepalese population often faces high cost, unreliable supply through overloaded grids and low load factors, and operation and management challenges (NEA, 2021). The NEA (2021) further intend to incorporate information technologies into their energy planning processes. As off-grid systems are often the most adequate solution for remote, mountainous areas in Nepal, the authors chose Solukhumbu for their applicability check. To generate load profiles for a representative village of 20 households, the survey Multi-Tier Framework for Measuring Energy Access by ESMAP and World Bank (2017) was analyzed with the software STATA. Enriched with assumptions from the literature, the authors then developed a demand profile, which was subsequently fed to the load profile generator RAMP by Lombardi et al. (2019). For the multi-year simulation, a project length of 30 years was chosen. Load changes were applied that reflect appliance ownership of developed regions in Nepal and increase rates that are typically found in areas that are electrified for the first time. Then, five different decentralized energy systems with varying energy technologies in different sizes comprising of photovoltaic systems, diesel generators, locally producible wind turbines, and battery storage were constructed.

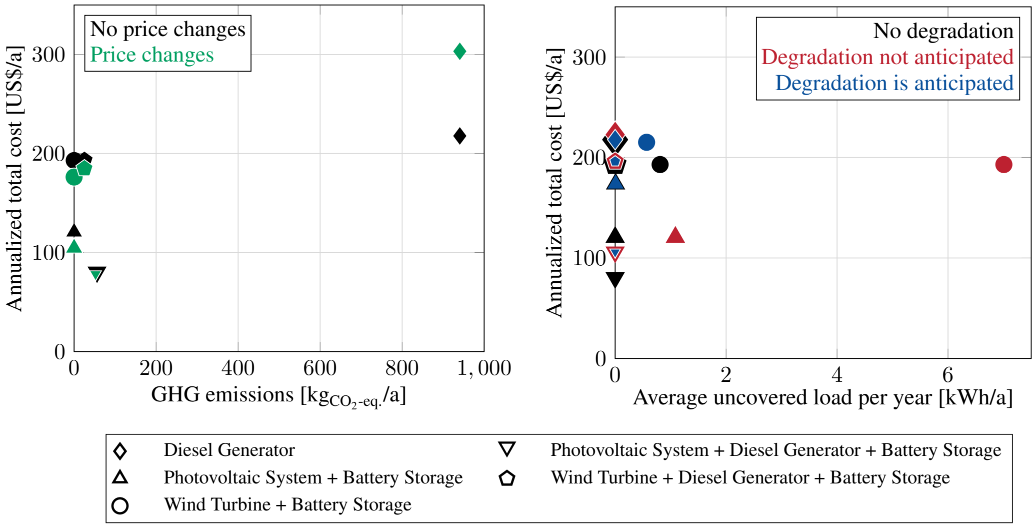


Figure 11: Economic and load coverage impacts of price changes (left) and components' degradation (right) by Eckhoff et al. (2022)

The authors state that the results in Figures 11 and 12 highlight the economic and ecological advantage of renewable energy technologies in contrast to fossil fuel solutions. With the expectation of higher fuel prices and lower installation cost of renewable energy technologies, these benefits would rise as political risks through import dependencies as well as energy induced poverty is mitigated. Elevated future demands and technology degradation need to be anticipated when sizing renewable energy technologies to avoid the need of increasing supply from traditional solutions with the corresponding negative environmental impacts. Regarding social factors, NESSI4D$^+$ helps to inform, engage, and empower local stakeholders, financiers, and investors by illustrating present and future needs and impacts. The demonstration depicted NESSI4D$^+$'s ability to account for site-, user-, and time-specific conditions and temporal variations while maintaining usability, flexibility, and detail. The authors highlight the relevance of considering time variations as called for by, e.g., Fioriti et al. (2021). The software is, thus, useful to reduce the complexities of energy system planning by exposing economic and ecological present and future impacts as called for by the SDGs and desired DSS by governments. Nevertheless, the authors acknowledge that the methods used to depict uncertainties are not exclusive. Changes may fluctuate or stagnate over time, expected weather changes including extreme events were omitted, and capacity and efficiency changes through new technologies as well as impacts of usage behavior were neglected.

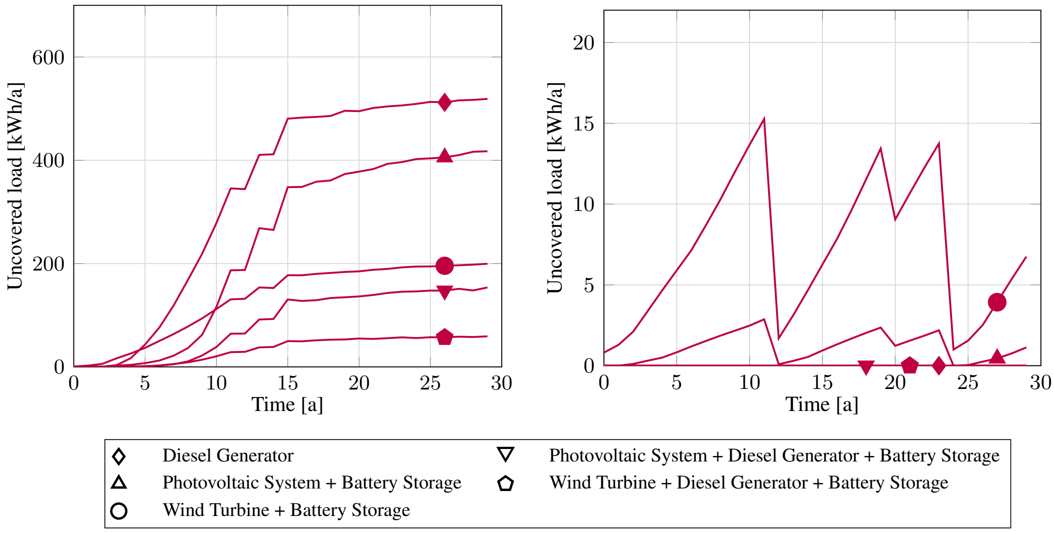


Figure 12: Uncovered load per year when load increases (left) or components' degradation (right) is not considered in the technologies' sizing by Eckhoff et al. (2022)

4.2.3 Design Cycle 3: Accessibility through Web Application

In the paper *Accessible Decision Support for Sustainable Energy Systems in Developing Countries*, Hart et al. (2022) describe NESSI's third design cycle which focuses on its accessibility. Access to reliable electricity supply is essential for digitization, competing in a globalized world, economic growth, and human development (UNDP, 2016). It is argued that stakeholders in developing countries are challenged by economic barriers, lack of qualitative data, and inadequate energy policies. Thus, DSS for developing countries must become accessible, usable, and cost-effective. However, established tools often require expert knowledge, apply optimization algorithms that require high computing power and time, and/ or are commercial (Hart et al., 2022). Thus, the authors further developed the software toward NESSI4D$^{\text{web+}}$ following Figure 13.

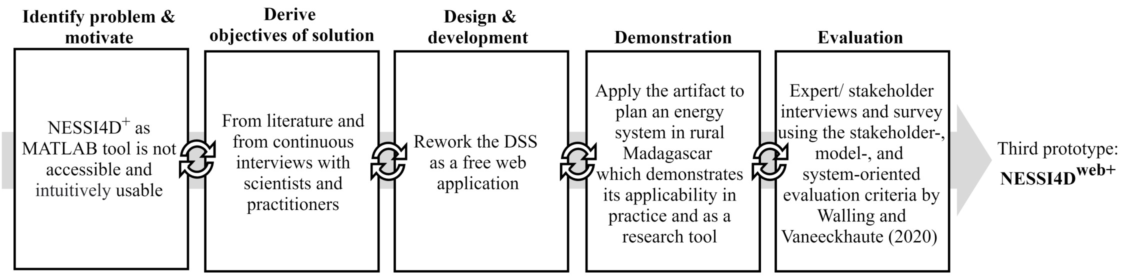


Figure 13: DSR cycle 3 toward NESSI4D$^{\text{web+}}$ adapted from Hart et al. (2022)

Previous versions of NESSI were developed with the software MATLAB App Designer, see Eckhoff et al. (2022) and Hart, Eckhoff, and Breitner (2023b). In this work, the authors reworked the software using the open-source programming language Python (v3.8). They chose the framework Django (v3.1.6), database PostgreSQL 13, and dockerized the backend to enable portability and development on various devices. The server runs on Linux distribution Debian 10. The web tool is available at https://nessi.iwi.uni-hannover.de/en. Strong emphasize was put on a high-quality, modern, and interactive GUI, which is adaptable to all screen sizes. To enhance usability and account for various literacy levels, the authors provided a manual, user flow, help texts, and tool tips. They additionally included adjustable templates and expert settings that refine the level of detail. When switching currencies, automatic conversion factors are applied. When the user desires to save, compare, and/ or share scenarios, a user account must be established. Additionally, all results can be downloaded in Excel format for further analyses. Global location-specific weather data is now automatically retrieved from the NASA Merra-2 dataset. The neighborhood model was reworked to increase usability. Lastly, a feedback button was added to ensure continuous improvements through user recommendations.

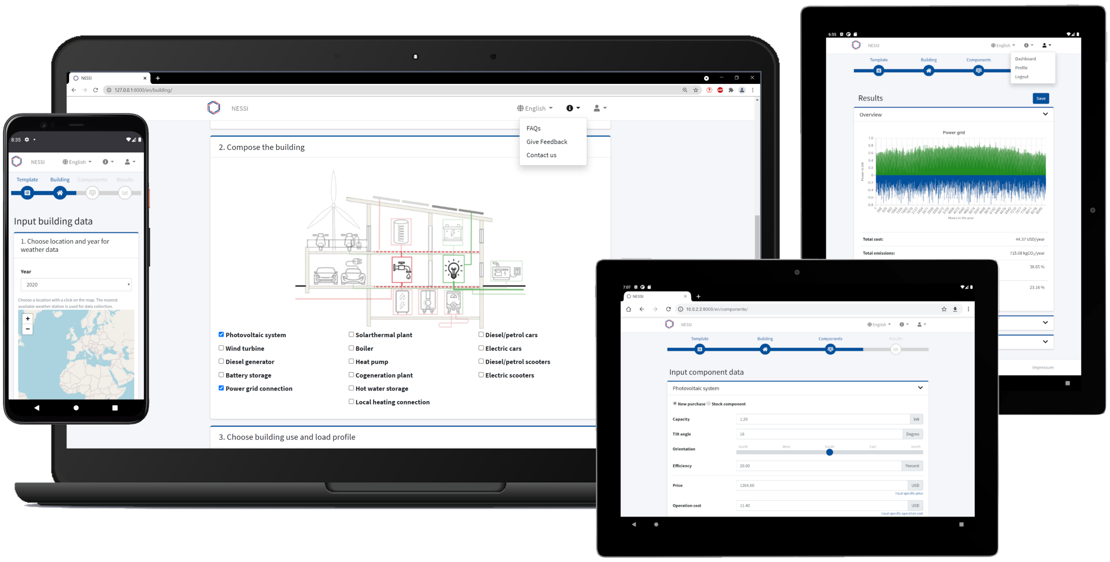


Figure 14: Exemplary screenshots of NESSI4D$^{\text{web+}}$ on various devices by Hart et al. (2022)

Subsequently, the authors demonstrated the tool's functionality, usability, and accessibility for stakeholders in developing countries on a representative village in Ambovombe, Madagascar. By assessing the countries energy-related conditions and goals, the authors found a low overall electrification rate, high reliance on fossil fuel imports, and commitments toward renewable energies (Ministry of Energy and Hydrocarbons, 2022; Surroop & Raghoo, 2018). Thus, the extension of a power grid with the development of island microgrids powered by fossil and/ or renewable energies was compared. Using any electronic device with internet connection, the user finds a general explanation and user manual of NESSI4D$^{\text{web+}}$, published articles, and two buttons leading to either the neighborhood or building simulation. The user may choose between the languages English and German and optionally create an account. Clicking on the neighborhood simulation, the user is led through the respective user flow with four steps as depicted in Figure 15.

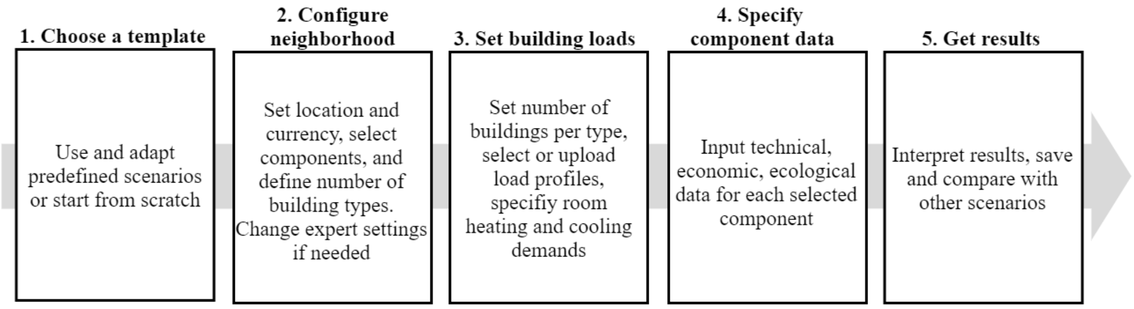


Figure 15: User flow of the neighborhood simulation adapted from Hart et al. (2022)

In Step 1), the user chooses between several adjustable templates and blank simulations. Step 2) guides through location, currency, component, infrastructure, and load profile selection. For this case, the user chooses Ambovombe, Madagascar, USD, electric infrastructure, and different compositions of wind turbines, photovoltaic systems, and battery storage. In the expert settings, they change the project length, interest rate, and investment for the island grid, to reflect the case and omit the multi-year option. They then construct demand profiles by analyzing energy demand data of Madagasi households by the World Bank which were then fed into the software RAMP (Enclude BV, 2018). 30 households of equally low and lower-middle-income group as well as an administration office, and a school, were analyzed. Thus, the user uploads the respective load profiles in Step 3). In Step 4), the user inserts component specific technological, environmental, and economic inputs before retrieving the results which are depicted in Figure 16.

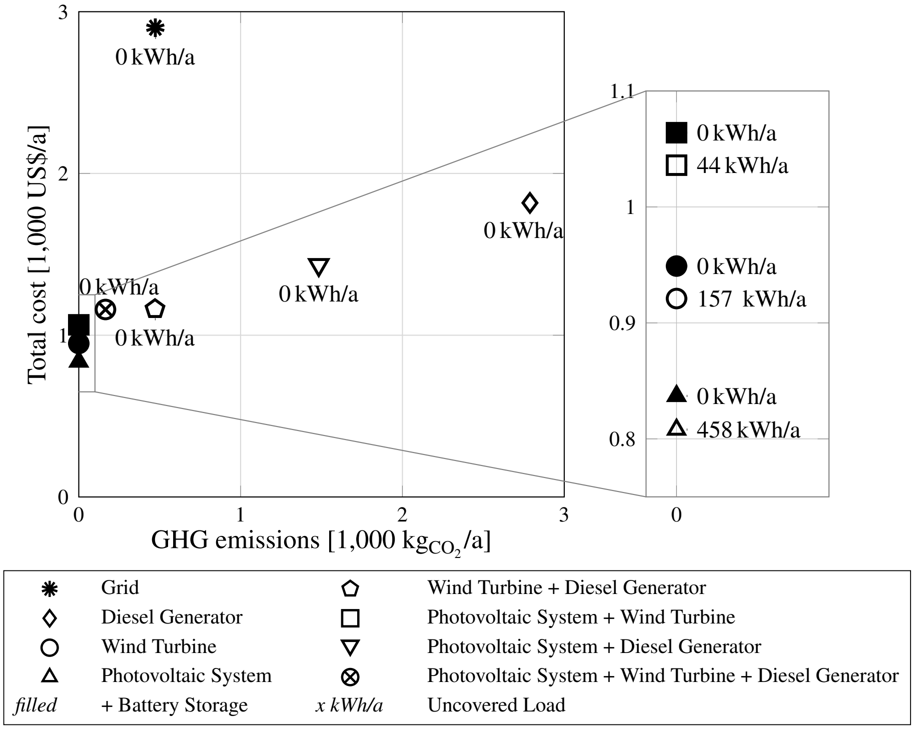


Figure 16: Simulation results adapted from Hart et al. (2022)

The results depict the environmental benefits of renewable technologies as grid and fossil fuel supplied technologies, i.e., the grid and diesel generator, emit direct and indirect GHG. Economically, fossil fuels and grid extensions are relatively more expensive due to the remoteness of the country and specific location. The authors further elaborated on the benefits of renewable supply to minimize import dependencies and mining with the increasing electricity demands. As renewable energy technologies are able to cover the full load, their benefits in regard to supply reliability and independence, specifically in the face of eroding national supplies, is highlighted. Nevertheless, the investment burdens for individual households and communities are acknowledged and supporting governmental policies, e.g., FITs, called for. NESSI4D$^{\text{web+}}$'s flexibility further allowed the user to analyze alternative technologies, such as second-life batteries and locally producible technologies, which have an impact on social factors. The former is locally available and may facilitate rural acceptance, whereas the latter may create job opportunities for distribution, installation, and repair, encourage entrepreneurship, and enable knowledge transfer.

Thus, the authors acknowledge the tool's ability to reveal the interrelations of energy technologies and their economic, environmental, and social impacts. Users are encouraged to further analyze, e.g., rising demands, fossil fuel consumption, and governmental policies. Overall, the tool's validity was demonstrated, and the benefits of an accessible and usable software underlined. Nevertheless, although the tool was made more accessible through a modern GUI and its mobile-first, no-cost approach, the authors highlight barriers in terms of device and internet dependency, literacy, electricity availability, and overall complexity. Prior limitations in terms of assumptions, omitted factors, and the quality of input data still significantly influence the model's results.

4.2.4 Design Cycle 4: Facilitating Load Profile Generation

The size and capacity of renewable energy technologies is determined by the magnitude and temporal distribution of energy demand, especially at peak times. Thereby, over-sizing leads to high cost and under-sizing entails unreliable supply, dissatisfaction, and greater use of harmful fossil fuels (Few et al., 2022; Herraiz-Cañete et al., 2022). The temporal distribution of electricity demand is critical to achieving a balance between power generation, distribution, and storage. Due to the lack of detailed, accessible energy demand data and challenges in modeling thereof, these are often only roughly estimated, neglecting local conditions, temporal variations, and uncertainties (Proedrou, 2021). Some DSS include load profiles from urban, industrialized countries, enable the expansion of daily to yearly load profiles, and/ or allow to upload own data. These options are often not suitable for rural developing countries with low data availability. Specific load profile generators require detailed input data retrieved from, e.g., activity diaries or national time-use surveys, or programming knowledge. For instance, RAMP, which has proven useful in previous work, lacks accessibility because it requires knowledge of the programming language Python due to the lack of a GUI. Furthermore, there is a lack of available software links between energy system simulations and load profile generators that provide the required level of detail, open-source availability, or ease of use (Hart, Eckhoff, & Breitner, 2023a). Next to this lack of tools, experts recommended the facilitation of load profile generation, specifically for applications in developing countries (Hart et al., 2022). Thus, in the paper *Sustainable Energy System Planning in Developing Countries: Facilitating Load Profile Generation in Energy System Simulations*, Hart, Eckhoff, and Breitner (2023a), developed an interface for the open-source software program RAMP by (Lombardi et al., 2019) and linked it with NESSI following Figure 17.

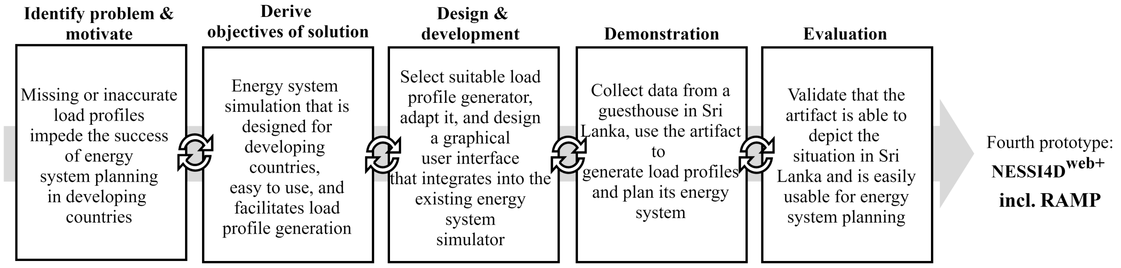
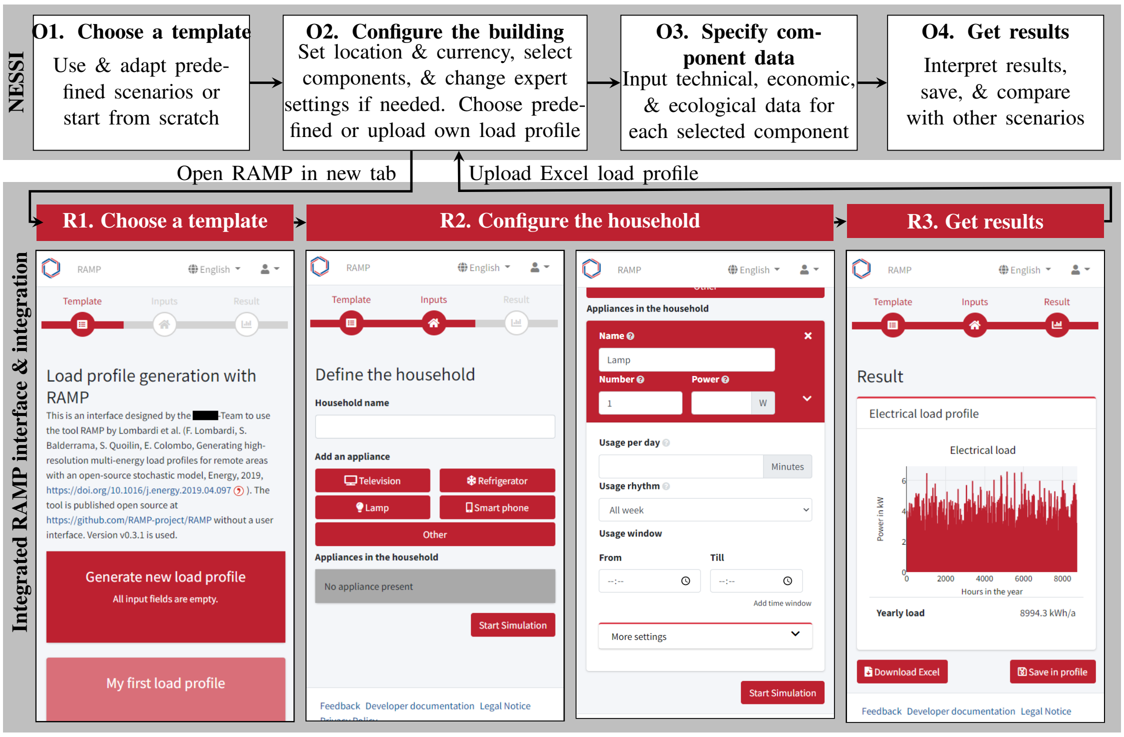


Figure 17: DSR cycle 4 linking RAMP by Lombardi et al. (2019) to NESSI adapted from Hart, Eckhoff, and Breitner (2023a)

To ensure the independence of both software applications, RAMP v0.3.1 was integrated as a standalone application in the form of a sub-page for NESSI. In order to be able to operate RAMP via the web interface, a Python dictionary is generated from the input data which is then transferred to RAMP. A custom post-processing script was developed to convert load profiles into the format required by NESSI. The authors created GUIs that allow the user to select templates or start from the ground up, define device properties and usage patterns, and adjust various parameters. The resulting load profile is then displayed graphically and can be downloaded in Excel format and/ or stored as a template in NESSI's user profile. To provide a sense of affiliation, the design, level of interactivity, type and depth of support, and user flow were chosen to be similar to NESSI. See Figure 18 for a graphical representation of the user flow and GUI in the building simulation.

For the applicability check, the authors chose Sri Lanka where severe economic challenges coupled with large import dependencies have led to serious shortages of food, medicine, as well as energy and electricity supply. In view of the government's objective to reduce GHG emissions, increase the share of renewable energy production and reduce dependencies, decentralized renewable energy systems offer a suitable solution (Balderrama et al., 2020; Danthurebandara & Rajapaksha, 2019). In Sri Lanka detailed load profiles are particularly essential in view of increasing electricity consumption, changing demand patterns, industrialization, and modernization to analyze adequate energy systems (Athukorala et al., 2019; Jayasinghe et al., 2018). Hart, Eckhoff, and Breitner (2023a) put their emphasis on an industry characterized by high financial constraints, considerable electricity demand, and strong dependence on its reliability, i.e., the tourism industry. They found that the type and number of existing appliances and the willingness and ability of owners to invest in new, modern appliances differ greatly between guesthouses. This underlines the need for up-to-date, non-standardized, and detailed energy demand time series.

To assess the applicability of the tool, the authors first conducted interviews with guesthouse owners regarding their ownership and usage behavior of electronic devices in Sri Lanka. They found significant differences in device ownership and use among guesthouses based on size, amenities, hours of operation, and service offerings, underscoring the importance of individualized



Load profile generation with RAMP

This is an interface designed by the [redacted]-Team to use the tool RAMP by Lombardi et al. (F. Lombardi, S. Balderrama, S. Quoilin, E. Colombo, Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model, Energy, 2019, https://doi.org/10.1016/j.energy.2019.04.097). The tool is published open source at https://github.com/RAMP-project/RAMP without a user interface. Version v0.3.1 is used.

Result

Yearly load: 8994.3 kWh/a

Figure 18: GUI and user flow integration in building simulation of RAMP into NESSI by Hart et al. (2022)

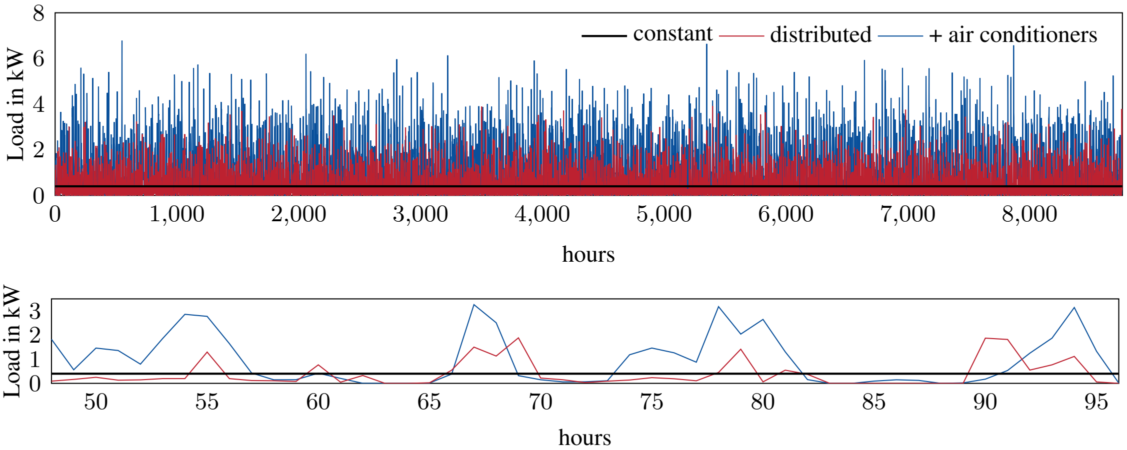


Figure 19: Load profiles of an exemplary guesthouse by Hart, Eckhoff, and Breitner (2023a)

and detailed load profiles. For the simulation, the effects of different load profile distributions and sizes were compared with a with constant load profile and those including additional appliances. Figure 19 shows the results of the whole year (8,760 hours) and two random days thereof (i.e., 48 hours). The authors concluded that including two air conditioners more than doubles the demand, specifically during peak times. Furthermore, the assumptions made previously are confirmed as peak loads can be observed in the morning and evening. The authors then simulated different renewable energy systems (e.g., photovoltaic system and wind turbine) and compared the results with traditional solutions (e.g., diesel generator, grid connection with power outages). They found that the distribution and magnitude of load profiles significantly impacts the energy system's economic feasibility, environmental sustainability, energy security, and dependency. Storage systems or flexible technologies are required to shift or generate electricity to times when needed. Power outages, specifically during peak times, must further be met with additional technologies. Diesel generators can ensure a reliable supply during demand peaks, uncertainties, and supply shocks. Thus, the authors confirmed the hypothesis, underlined by, e.g., Proedrou (2021), that detailed load profiles are essential for the choice and sizing of energy technologies and validate the importance of this feature in energy DSS. Nevertheless, using modeled data will always be subject to inconsistencies to reality. Thus, it is essential to closely monitor and evaluate results of RAMP and NESSI. Further, this approach's usability decreases with the number of distinct appliances which may inhibit its usage in certain scenarios such as commercial buildings.

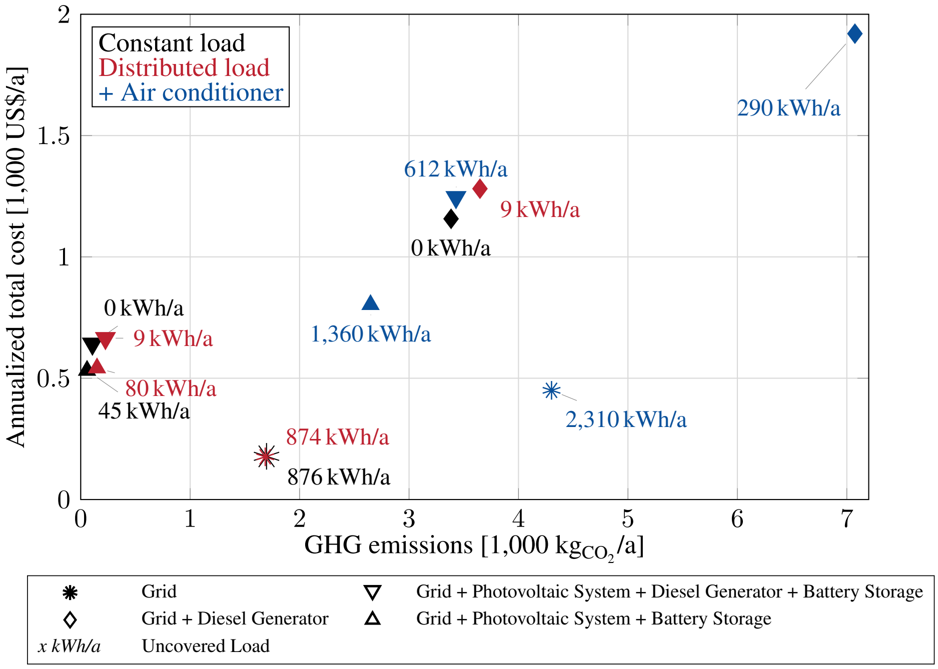


Figure 20: Energy supply scenarios for an exemplary guesthouse by Hart, Eckhoff, and Breitner (2023a)

Through this work, a collaboration with the open-source RAMP project team comprising of faculty members and employees at TU Delft (The Netherlands), Reiner Lemoine Institute (Germany), VITO (Belgium), University of Liège (Belgium), University of Cape Town (South Africa), and Universidad Mayor de San Simon (Bolivia) emerged. Jointly, this design cycle's work was added to RAMP's open-source repository (https://github.com/RAMP-project/RAMP) and is presented by Lombardi et al. (2024).

4.2.5 Design Cycle 5: Incorporating the Social Dimension

In line with the focus on economic and ecological aspects in public and scientific discussions, social criteria are often neglected when considering energy systems and developing energy system models, see Section 2.2. Yet this dimension is often central to long-term, successful energy development projects, and its disregard has proven to influence local acceptance, collaboration, and participation negatively, especially in developing countries (Evans et al., 2009; Urmee & Md, 2016). One bottleneck is the lack of a coherent and clear definition, as well as philosophical and conceptual difficulties, when it comes to social sustainability and its evaluation (Galán-Martín et al., 2016). In the paper *Threefold Sustainable Neighborhood Energy Systems: Depicting Social Criteria in Decision Support Systems*, Hart, Eckhoff, Schäl, and Breitner (2023), thus, established a framework for assessing social sustainability and implemented the derived criteria and indicators in NESSI following Figure 21.

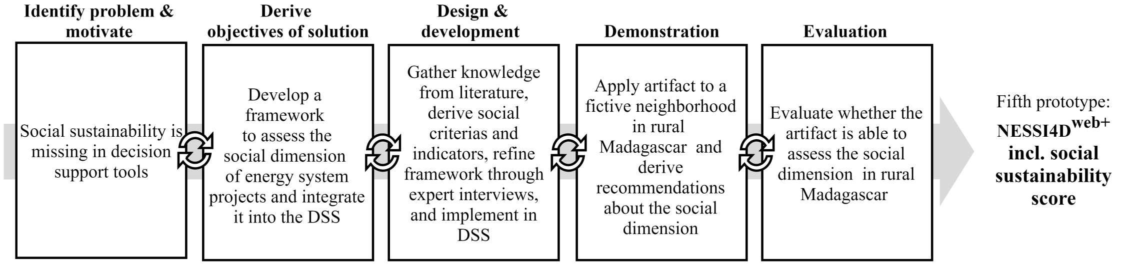
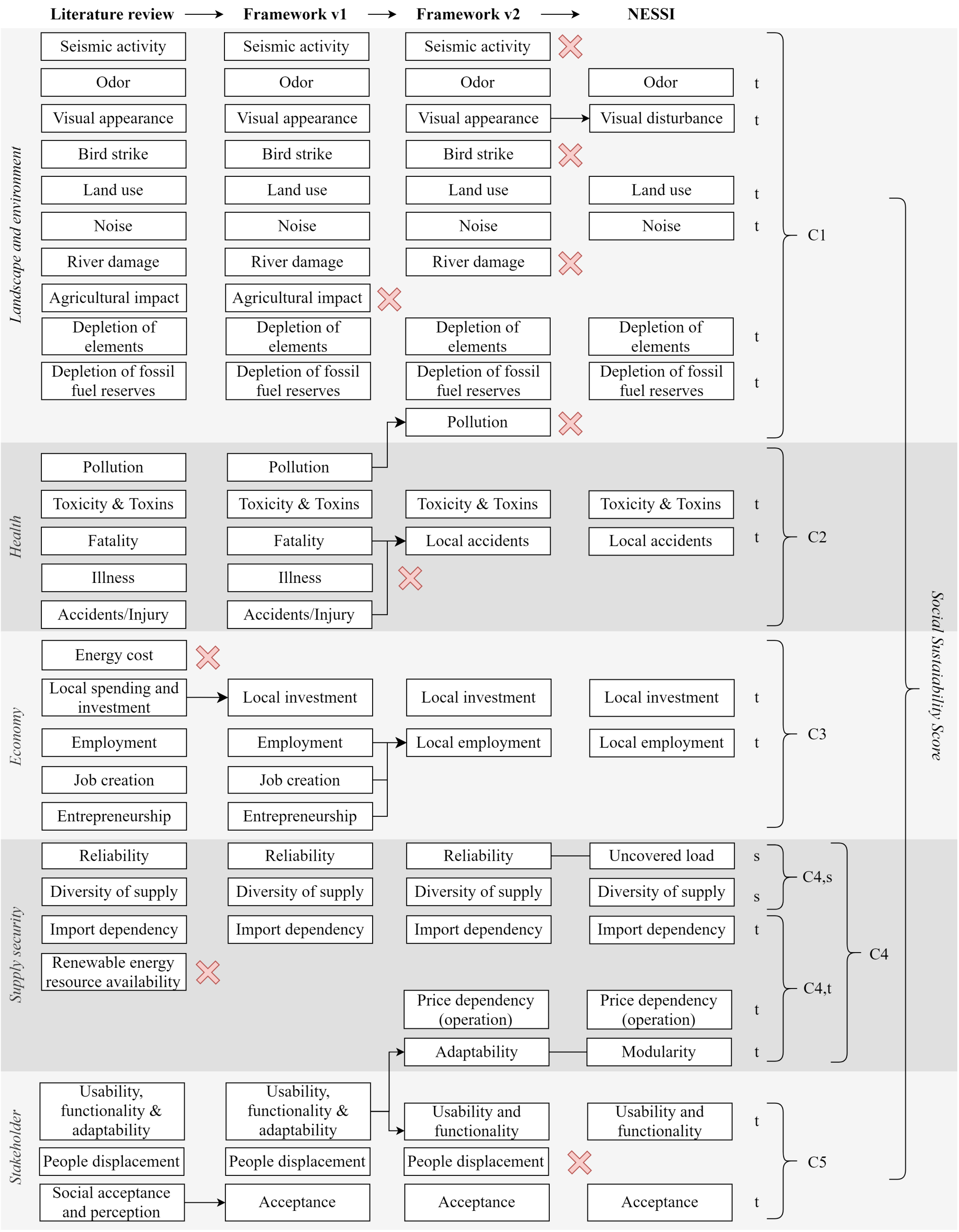


Figure 21: DSR cycle 5 including the Social Sustainability Score in NESSI adapted from Hart, Eckhoff, Schäl, and Breitner (2023)

First, the authors conducted a systematic literature review according to Watson and Webster (2020), vom Brocke et al. (2009), and Webster and Watson (2002). They analyzed 669 papers on social criteria, indicators, and their respective calculations. Throughout three phases, the authors then evaluated the indicators' fit for DSS in general and NESSI specifically by conducting semi-structured expert interviews and user testing. Where necessary, the authors redefined, refined, or excluded respective factors. Figure 22 depicts the framework development process. Afterward, the authors integrated the remaining indicators in the neighborhood simulation of NESSI using five-step ordinal scales for all technology-related indicators. The calculation of the Social Sustainability Score is based on the weighted sum method by Maxim (2014) and multi-attribute value theory by Atilgan and Azapagic (2016). The Social Sustainability Score is calculated as follows:

$$SocialSustainabilityScore = \sum_{n \in N} C_n w_n \; with \; C_n = \frac{\sum_{m \in M_{n,t}} \times I_{m,t}^{norm}}{M_{n,t} \times T} + \frac{\sum_{m \in M_{n,s}} \times I_{m,s}^{norm}}{M_{n,s}}$$

with N = number of criteria, C_n = value of criterion n, w_n = weight of criterion n, M_n = number of indicators related to criterion n, $I_{m,t/s}^{norm}$ = normalized indicator of t or s, and T = number of technologies. Ordinal scales are assigned values 0, 0.25, 0.5, 0.75, 1. 0 has a negative impact which gradually changes to a positive impact the higher the value. Additionally, weights and bounds are included to allow for linear normalization. The results are then depicted in form of a bar chart.



* Abbrevations: t = per technology, s = system-wide, C = Criteria

Figure 22: Framework development adapted from Hart, Eckhoff, Schäl, and Breitner (2023)

The authors then evaluated NESSI's extension with an applicability check. To highlight the impact of this dimension, the authors extended the existing applicability check conducted by Hart et al. (2022) and simulated the same representative Madagasi neighborhood. As shown in Figure 23, the relative benefit of each technology shifts when adding the social dimensions compared to prior results by Hart et al. (2022). Photovoltaic systems, which were considered the most desirable option, show relative negative impacts in terms of investment, employment, and usability. Wind turbines gain desirability due to their relatively easier use and option to partly produce them locally. Energy systems, which include diesel generators instead of battery storage, have a higher score due to high stakeholder (i.e., acceptance, usability, and functionality) and economy scores (i.e., employment and investment). These factors outweigh the negative health and landscape scores. Supply by the central power grid remains the most unfavorable option due to their negative influence on import dependencies, prices, and employment. The authors, thus, validated the initiation of this design cycle and the importance of considering this dimension in DSS for planning hybrid energy systems. However, they highlight that the results strongly depend on the individual beliefs, preferences, and perceptions as they are often not objectively quantifiable. They further acknowledge the vagueness of these results due to poor data availability and the use of ordinal scales. A third obstacle is the correlation of several indicators and the three sustainability dimensions. For instance, involving local stakeholders in the planning process has shown to increase acceptability. Further, the authors found that some research includes energy cost, pollution, and renewable energy resource availability in the social dimension whereas the authors allocated it in the other two dimensions. Therefore, it remains to be discussed whether the separation of the dimensions is suitable or if an all-encompassing score is more beneficial. The authors, therefore, invite stakeholders and scholars to explore this domain, in order to critically examine the derived methodology and together construct a refined definition, framework, and DSS.

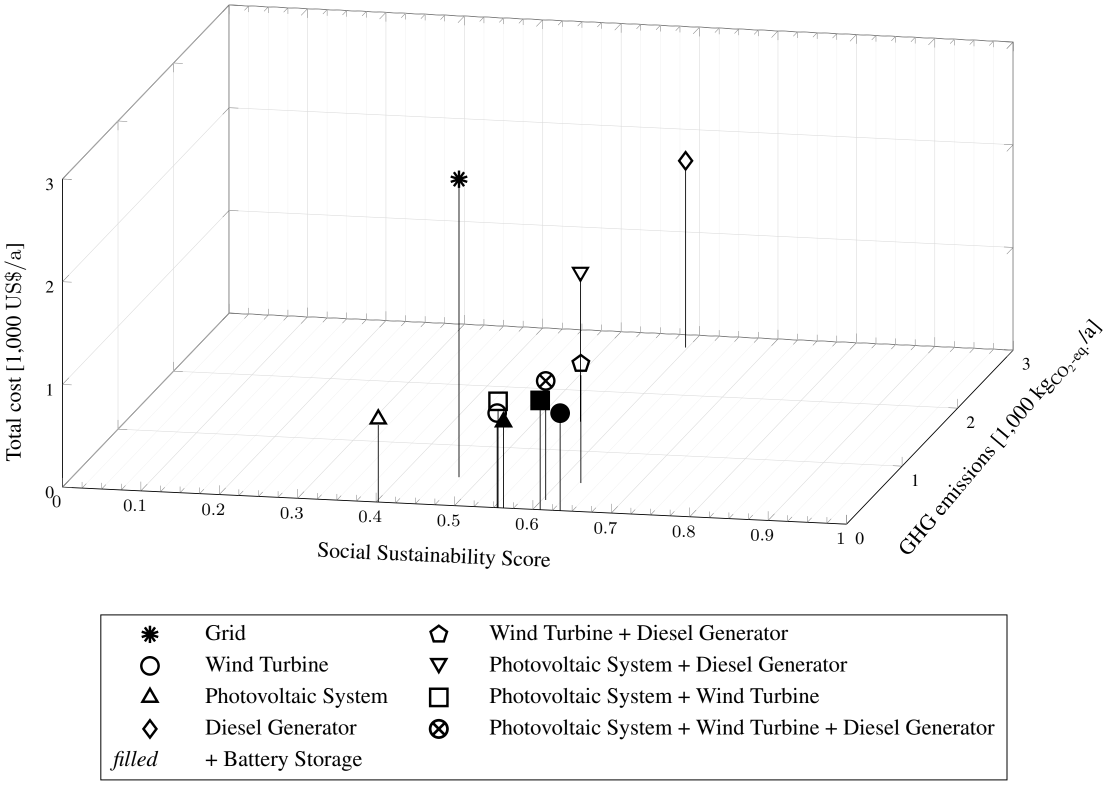


Figure 23: Threefold sustainability assessment of neighborhood energy systems in Ambovombe, Madagascar adapted from Hart, Eckhoff, Schäl, and Breitner (2023)

4.3 NESSI's Functionalities, Simulation Procedure, and Underlying Calculations

Having elaborated on the requirements, software development, and evaluation, NESSI's current functionalities as well as underlying calculation are summarized and a short demonstration provided. This follows from the experts' requirement and Walling and Vaneeckhaute (2020) to enhance transparency, credibility, and trust (Hart et al., 2022). This section is based on the article *Open Access Decision Support for Sustainable Buildings and Neighborhoods: The Nano Energy System Simulator NESSI* by Eckhoff et al. (2023), but also elaborates on features added after its publication.

NESSI allows users to evaluate energy systems for buildings (i.e., single and multiple family homes, commercial buildings, mixed buildings) and small-scale neighborhoods. These may comprise of a combination of fourteen renewable and conventional energy generating, storing, and consuming technologies including photovoltaic systems (multiple), a wind turbine, solar thermal system, heat pump, boiler, co-generation plant, diesel generator, battery storage, hot drinking water storage, space heating water storage, air conditioner, two- and four-wheeled fuel-based or electric vehicles as well as a connection to an external heating and/ or power grid. Both, single and multi-year options (see Subsection 4.2.2 and Eckhoff et al., 2022), are calculated in hourly time steps and their simulation takes up to five seconds. As elaborate on in Subsection 4.2.4 and in Hart et al. (2022), the tool is programmed in Python 3.10 using the Django 3.1.6 framework, database PostgreSQL 13, and a dockerized the backend to enable portability and development on various devices. The server runs on Linux distribution Debian 10. Weather data is obtained from NASA Merra-2 and load profiles are pre-generated and stored using the LoadProfileGenerator by Pflugradt et al. (2022), the German energy suppliers VDEW (1999) or with the included RAMP interface (see Subsection 4.2.3 and Hart, Eckhoff, & Breitner, 2023a). The software architecture is depicted in Figure 24.

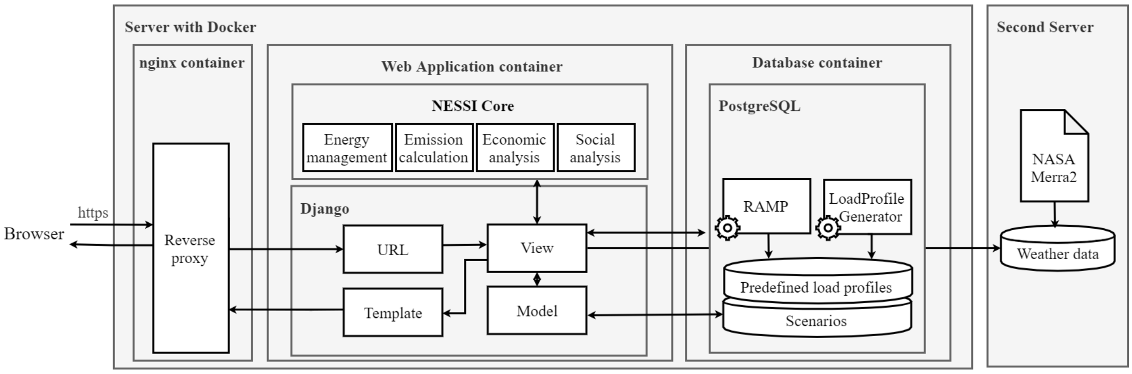


Figure 24: Software architecture adapted from Eckhoff et al. (2023)

The simulation procedure differs for buildings and neighborhoods in the number of building objects. In the first step, four load arrays are created: hot water and electricity arrays are calculated from the load profiles, whereas space heating and cooling is based on the Association of German Engineers (VDI) guideline 2067/DIN 4108 T6. If new technologies are purchased, a reference scenario is created in the second step to assess the investment economically by including all pre-owned components. A new boiler is included in the reference scenario if no heat generating technology is selected. Third, in the pre-processing phase, electric vehicle loads as well as photovoltaic system, solar thermal, and wind turbine yields are calculated using (among others), the *pvlib* (link) and *windpowerlib* (link) libraries. The simulation procedure is depicted in Figure 25.

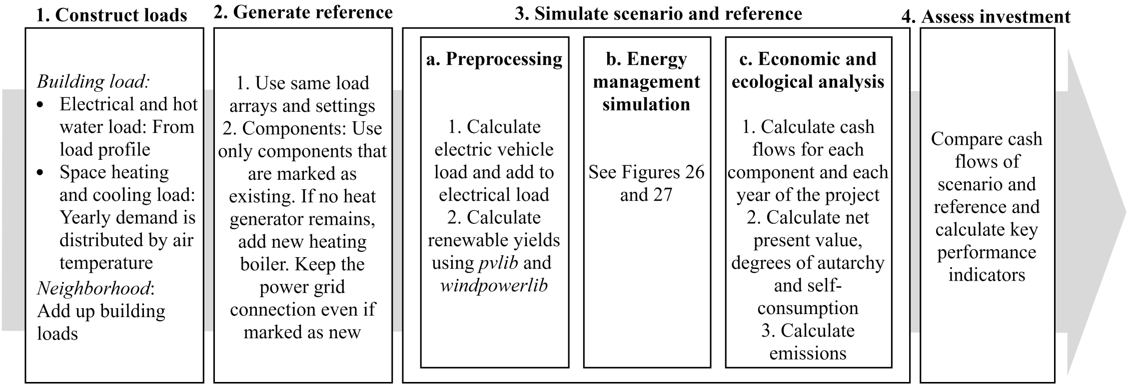


Figure 25: Four-stage simulation procedure adapter from Eckhoff et al. (2023)

The calculation follows a rule-based energy management simulation which ranks the component's calculation for optimal yields from renewable energy technologies and is summarized in Figures 26 and 27. In each hourly time step, the software checks if a component is included. Hot drinking water takes priority over space heating. When selecting multi-year simulations, the deterioration rate is considered for each component and simulated year. Furthermore, the state of charge is calculated for energy storing components each passing hour. Afterward, economic, ecological, and social calculations are conducted to present the cash flow including re-investments, revenues, operation and management as well as investment cost, residual values, the social sustainability score, and various key performance indicators (i.e., net present value, degree of self-sufficiency and self-consumption, GHG emissions). Additionally, the reference scenario is given for comparison. It further provides information on cumulative savings, amortization period, internal return on investment as well as changes in degree of self-sufficiency, self-consumption, and GHG emissions. For more detail, please read Eckhoff et al. (2023).

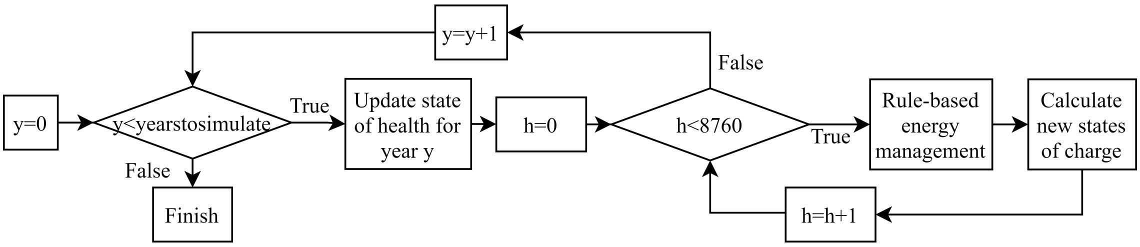


Figure 26: Energy management simulation adapted from Eckhoff et al. (2023)

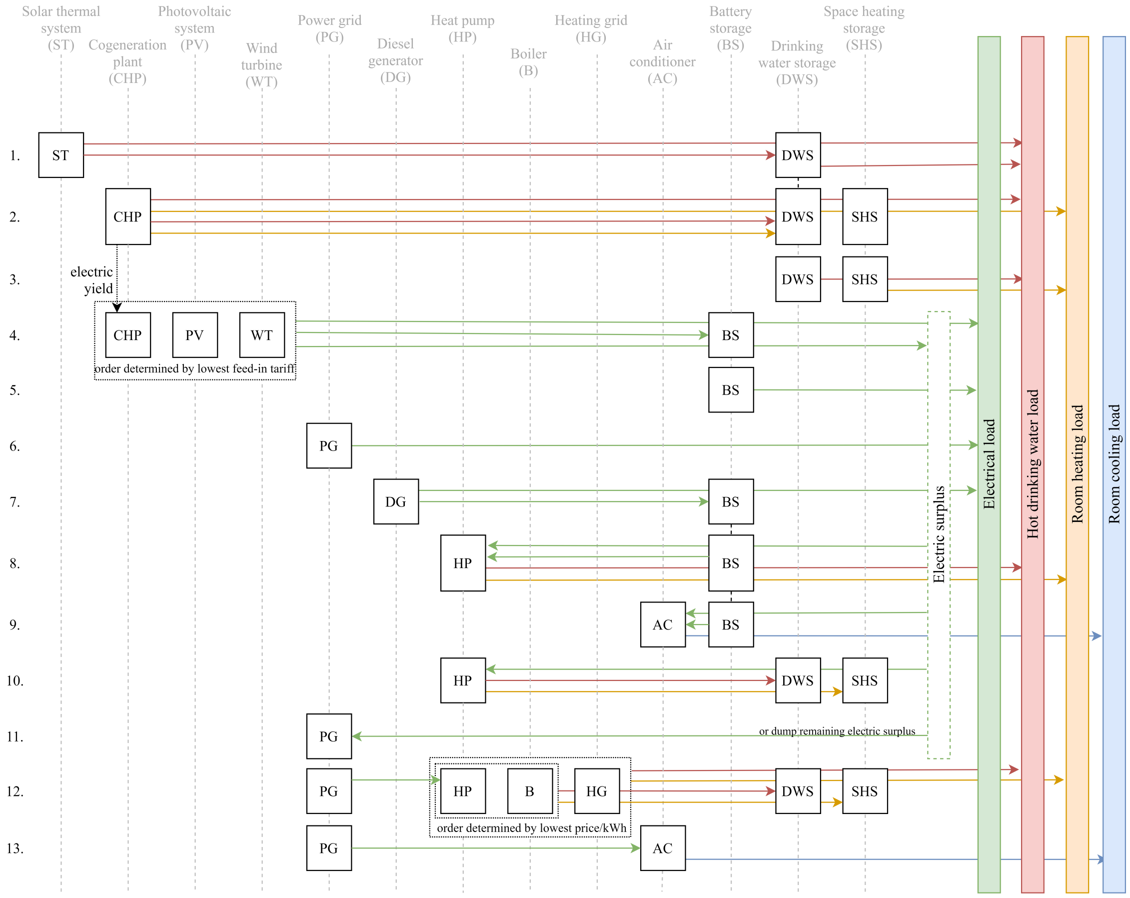
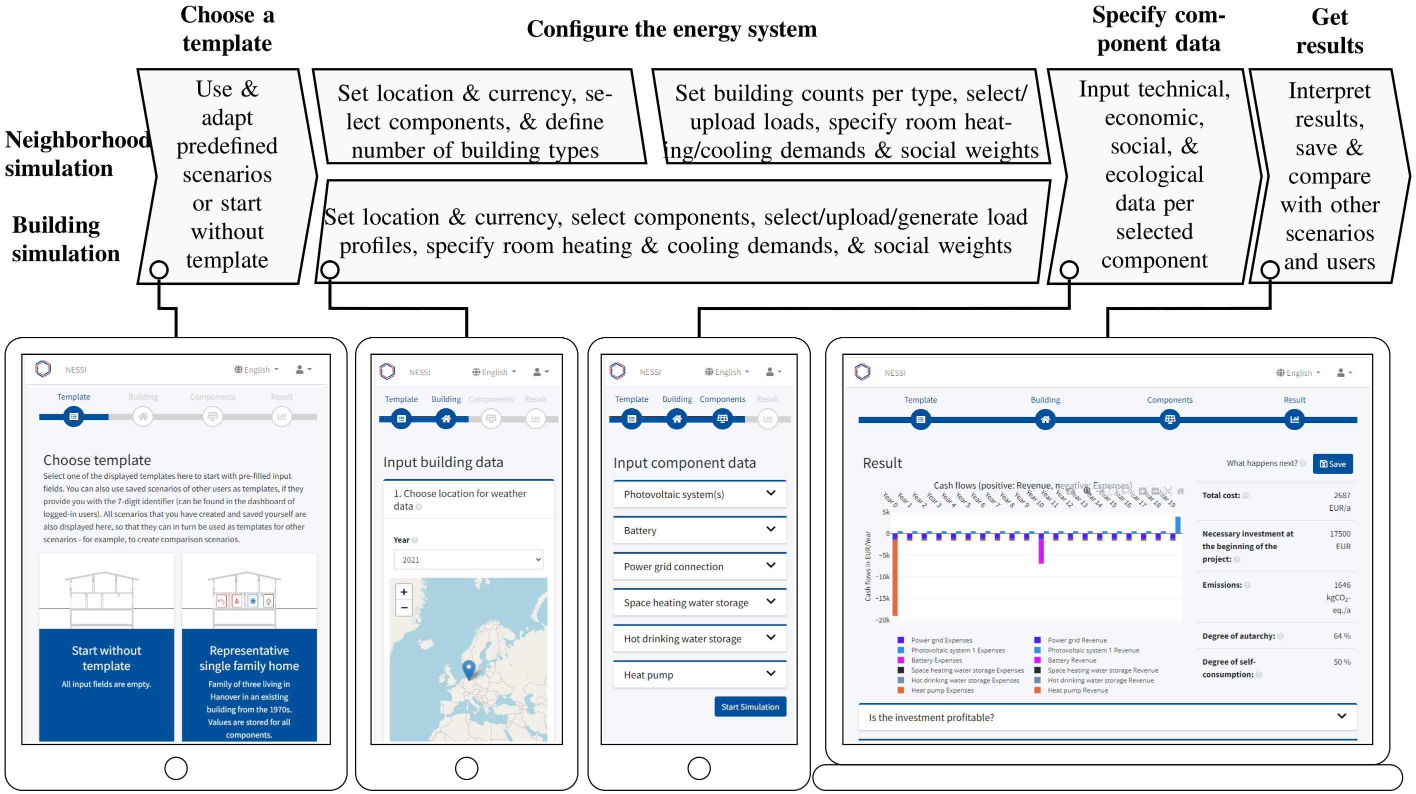


Figure 27: Hourly rule-based energy management by Eckhoff et al. (2023)

To increase the tool's usability, a strong emphasis on a modern, interactive interface, which is adaptable to all screen sizes was put throughout the whole development process. Several features for guidance such as general explanation of the tool, user manual, and a list of related research publications were included. The user is further carefully guided through the simulation via five steps, i.e., *Templates*, *Neighborhood* (if applicable), *Building*, *Components*, and *Results*, with a corresponding progress bar, see Figure 28. On the page *Templates* pregenerated and saved templates are available whose inputs are prefilled and flexibly adaptable. Expert settings, i.e., project length, interest rate, automatic reference scenario generation, and the option to choose multi-year simulation, which are always prefilled, are provided. Additionally, each input is given a tooltip with further explanation. Further, the user is able to save scenarios in the *Dashboard* for comparison, future usage, or dissemination by copying an automatically created link. All results can be downloaded in Excel format. To validate the tool, the authors demonstrated a use case of a single family homeowner in Hanover, Germany evaluating an additional heat pump to an existing photovoltaic system with a battery storage.



Choose template

Select one of the displayed templates here to start with pre-filled input fields. You can also use saved scenarios of other users as templates, if they provide you with the 7-digit identifier (can be found in the dashboard of logged-in users). All scenarios that you have created and saved yourself are also displayed here, so that they can in turn be used as templates for other scenarios - for example, to create comparison scenarios.

Start without template
All input fields are empty.

Representative single family home
Family of three living in Hanover in an existing building from the 1970s. Values are stored for all components.

Input building data

1. Choose location for weather data

Year: 2021

Input component data

Photovoltaic system(s)
Battery
Power grid connection
Space heating water storage
Hot drinking water storage
Heat pump

Result

What happens next?

Total cost: 2687 EUR/a
Necessary investment at the beginning of the project: 17500 EUR
Emissions: 1646 kgCO$_2$-eq./a
Degree of autarchy: 64 %
Degree of self-consumption: 50 %

Is the investment profitable?

Figure 28: User flow of neighborhood and building simulation with exemplary screenshots on various devices by Eckhoff et al. (2023)

4.4 Case Studies

4.4.1 Thailand

Thailand's significant social and economic development in recent decades has led to a steady increase in energy demand. Household electricity consumption has increased by 54 % over the past ten years (Ministry of Energy Thailand, 2023; Phadkantha & Yamaka, 2022). This demand has been met primarily through increased production and import of fossil fuels, resulting in higher carbon emissions and potential threats to the country's energy security due to political market risks and dependence on other nations (IEA, 2023). In light of these risks and global disruptions such as the Covid-19 pandemic and the Russian invasion of Ukraine, the Thai government is committed to fostering energy resilience through locally generated, clean energy. This includes supporting communities to become prosumers of electricity through the use of small-scale renewable energy systems (Ministry of Energy Thailand, 2011). Thus, in the article *Fostering Energy Resilience in the Rural Thai Power System - A Case Study in Nakhon Phanom*, Hart and Breitner (2022) evaluated the opportunity of renewable energy systems in rural areas of Thailand.

The authors present a simulation study of different renewable energy systems for a remote community in northeastern Thailand. In an extensive literature review, they analyzed previous studies on appliance ownership and electricity consumption of the Thai population, noting research limitations such as lack of distinction between urban and rural households, exclusive focus on urban households, industries, educational institutions or the country as a whole, and small sample sizes (Hart & Breitner, 2022). They, therefore, synthesized detailed load profiles using the TVSEP (TVSEP, 2023). They analyzed data from 2008 to 2019 for a representative community in the Nakhon Phanom region. First, they examined the impact of changing housing conditions, household dynamics, and appliance ownership over a decade on renewable energy system planning in Nakhon Phanom. They found that the average per capita income has tripled over this period, while average house size has increased slightly. The majority of households are connected to the grid and used electricity mainly for lighting, with a shift from firewood to bottled gas for cooking. Ownership of electrical appliances increased, especially energy-intensive appliances such as refrigerators, rice cookers, and washing machines. In particular, the popularity of older technologies declined, while modern appliances became more desirable. The data highlights the need to consider trends in appliance ownership when designing sustainable, long-term energy systems. From these insights, the authors created a demand profile, which they enriched with information from other research and assumptions. They fed the resulting energy demand profile into the RAMP software by Lombardi et al. (2019) to generate minute-by-minute load profiles. To feed NESSI with the necessary inputs, they further carefully collected market data.

Conducting 56 simulations, the authors found that renewable energy, particularly the combination of wind turbines and photovoltaic systems, increases energy independence and reduce environmental impact. Nevertheless, this is not economically attractive without government subsidies. The results further suggest that battery systems are critical to the stakeholder's self-sufficiency but are cost-intensive. The results further suggest positive environmental impacts. However, NESSI4D does not consider their production and waste disposal which may give biased results.

Compared to carbon credits, FITs had the largest impact on renewable energy, which includes photovoltaic systems. Carbon credits were only effective at unusually high rates. They concluded that the most economically attractive renewable energy source is a combination of conventional grid, photovoltaic system, and battery storage, however, initial costs remain a barrier. They emphasized the importance of considering rising electricity demands and the role of the local communities in renewable energy projects. They recommended that policy makers introduce and promote photovoltaic system and battery storage, provide transparent and stable subsidies, and support disadvantaged communities with targeted financial and technical assistance.

4.4.2 Colombia

Despite the high potential of renewable energy systems, Colombia's total energy demand is largely met by fossil fuels. Identified as a country vulnerable to climate change, Colombia has, thus, committed to significant climate change targets, including a 51 % reduction in GHG emissions by 2030, carbon neutrality by 2050 and zero deforestation (Cámara de Comercio de Bogotá, 2022). To achieve these goals, the Colombian government is exploring distributed renewable energy systems. However, the deployment of these technologies is hindered by, e.g., a lack development of planning, financial investments, and synchronization between public and private projects (Gómez-Navarro & Ribó-Pérez, 2018). Several studies have evaluated the integration of renewable energy sources in the country, taking into account current and future energy needs and the economics of renewable energy production. However, these studies often rely on average load profiles, estimates, stochastic calculations, or outdated data to determine current energy demands (Redecker et al., 2023). Thus, in the article *Fostering Sustainability with Decentralized Renewable Energy for Developing Countries: A Case Study in Colombia*, Redecker et al. (2023) addressed this research need and closed the research gap by generating high resolution load profiles and evaluating the opportunity of renewable energy systems in the two Colombian cities Bogotá and Fusagasugá.

First, the authors conducted an online survey to collect data on residents' energy consumption, appliance ownership and usage as well as potential future purchases. The survey, conducted between June 8th, 2022, and June 27th, 2022, was completed by 54 of the 76 participants. The data showed that most households had a smartphone charger, a washing machine, a television, and a refrigerator. Mixers, hairdryers, and radios were found in only half of the households, while irons and laptop chargers were common. The ownership of heating and cooling systems was very low. The survey revealed differences in energy ownership and consumption between the two cities. In Bogotá, a larger urban city, the number of electrical appliances was higher than in Fusagasugá, a smaller rural town. For example, the total number of indoor light bulbs and chargers for phones, laptops, and tablets was significantly higher in Bogotá. Further, modern appliances for free time activities were more common in Bogotá. Thus, the authors confirmed the common conception that households in urban cities tend to be technologically more developed, which may be due to monetary capabilities and occupations.

Using this survey data, the authors then created two model communities and calculated their energy demand profiles. They found that the average annual electricity demand for the model community in Bogotá was 4.5 % higher than in Fusagasugá, a smaller discrepancy than expected due to the recognized differences in the number and usage of electrified technologies. They hypothesize that this may be due to the lower energy consumption of small electronic appliances, the longer use of energy-intensive appliances in Fusagasugá, and more modern, energy-efficient appliances in Bogotá.

After extensive market and literature search to feed NESSI, they found that energy systems with battery storage are the most suitable option. However, most renewable energy technologies generate excess electricity that battery storage capacities cannot always fully store, leading to greater dependence on the central grid. Comparing the cities of Fusagasugá and Bogotá, they found that due to different energy demands and weather conditions, the sizing and choice of renewable energy technologies vary. Thus, the comparison highlighted the importance of considering local conditions and individual requirements to optimize the economic and environmental outcomes of energy systems. Investigating FITs, they found a positive impact on overall cost. However, they state that higher FITs could discourage stakeholders from installing battery storage, increase dependence on the central grid, and elevate risks of grid overloads at peak times. They conclude that with NESSI, stakeholders in Colombia are supported to design their appropriate small-scale renewable energy systems. For this case specifically, they were able to identify photovoltaic systems as an option with significantly positive opportunities toward clean and cost-effective energy production.

5 Theory Building

5.1 Societal Sustainability Transformation in Developing Countries

The overall aim of this work is to support SDG 7 through bottom-up empowerment with the DSS NESSI. In the paper *Design Principles for Decision Support Systems Promoting Societal Sustainability Transformations in Developing Countries*, Hart et al. (2024) argued that on an abstracted level, NESSI contributes to the broader goal of improving and harmonizing interrelated economic, environmental, and social conditions as postulated by the SDGs. The authors refer to this as "societal sustainability transformation". In this regard, mathematical multi-dimensional DSSs are used as supporting tools. However, this work has proven that existing DSS often lack accessibility, detail, usability across different stakeholder groups, geographic and/ or sectoral coverage, and are often biased toward developed nations (see Subsection 2.2). Following Gregor et al. (2014) who state that design knowledge for information and communication technologies for development reduce the chance of failure, Hart et al. (2024) stipulate that DSS developers require guidance to create DSS that foster societal change toward sustainability for developing countries.

5.2 Related Literature

Applying a systematic literature search according to Watson and Webster (2020), vom Brocke et al. (2009) and Webster and Watson (2002), the authors discovered 132 articles about design theory in developing nations. They extracted six studies that develop design principles for IS toward societal transformations in developing countries, but none of them referred to sustainability transformation. To extract design principles or best practices, some researchers consult related literature, theory that already exists, and/ or interviews with stakeholders. They then create and assess a related artifact using this knowledge, see, e.g., Twomlow et al. (2022) or Robinson and Imran (2015). Other research approaches by e.g., Greve et al. (2020), Braa et al. (2023), Gregor et al. (2014) or Zaitsev and Mankinen (2022) comprised of creating a specific IT artifacts in order to develop design knowledge afterward. Nevertheless, the authors found that the outcomes were either too specific, not grounded, and/ or not applicable for their specific application class. It is noteworthy that there have not been retrospective evaluations of design theory development in any study.

5.3 Generalized Design Principles

Following Baskerville et al. (2018), Hart et al. (2024) abstract and reflect from the artifact's development process and derived a set of seven fundamental design principles from their collective experiences in identifying challenges, defining requirements, and engaging in five iterative design cycles. They oriented the formulation and presentation of the design principles on the structure of Gregor et al. (2020) and the re-usability criteria of Iivari et al. (2021). They then ground these principles in theory from the fields of natural and social sciences following Möller et al. (2022)'s fifth mechanism. For each design principle, they added several design features for further developer support, see Table 5.

Design Principle 1: Comprehensiveness

The World Commission on Environment defines sustainability as meeting present needs without compromising future generations, leading to the United Nations' 17 Sustainable Development Goals (United Nations, 2015). Sustainability involves interconnected elements such as environmental preservation, economic efficiency, and social equality, i.e., the Three-Pillar Model (Purvis et al., 2019). However, there is a noted deficiency in the attention given to the social aspect in public and scientific discourse (Hart, Eckhoff, Schäl, & Breitner, 2023). DSS often exclude social criteria, leading to low local acceptance and potential project failures (Evans et al., 2009; Urmee & Md, 2016). Therefore, the social dimension was incorporated in NESSI emphasizing, demonstrating, and proving its importance, see Hart, Eckhoff, Schäl, and Breitner (2023). Moreover, a fourth dimension, technology, was identified as key for project success (Al Irsyad et al., 2017). DSS must, therefore, consider engineering, economic, social, and environmental perspectives, especially in designing energy systems in developing countries.

Design Principle 2: Stakeholder Involvement

NESSI's development process identified four key stakeholder categories: impacted parties, opinion leaders, consultants, and decision-makers. However, the challenge of developing a DSS that is usable for both practice and research is stressed and, thereby, a narrow stakeholder definition advised. Grounded in the Participatory Action Research approach in research processes by Mumford (1983), the need for stakeholder involvement at all stages is underlined. This fosters shared responsibility, accountability, and engagement, reducing conflict and promoting perceived legitimacy of decisions (Mathur et al., 2008; Olphert & Damodaran, 2007). Local ownership and collective action need to be fostered, particularly in developing countries (Braa et al., 2023). Further, the need for early and continuous feedback loops, facilitated through presentations, public events, and interviews is stressed. Partnerships with businesses in developing countries and the inclusion of specific design features that foster collaboration between users are advocated.

Design Principle 3: Location Depictability

Existing DSS are often biased toward developed countries, which may lead to skewed results when applied in different contexts (Al Irsyad et al., 2017; Debnath & Mourshed, 2018; Gregor et al., 2014). Feedback from international experts and calls from IS scholars further highlighted the need for DSS to be tailored to local contexts, aligning with Contingency Theory (Hart et al., 2022; Reinking, 2012). It is emphasized that there is no one-size-fits-all solution, and the success of an intervention depends on the environment, organization, and decision-making style (Gordon & Miller, 1976). Supported by Gregor et al. (2014)'s recommendation to adapt existing tools, NESSI by Kraschewski et al. (2020) was adapted to address circumstances common in developing countries, such as specific technologies and economic conditions (see Hart, Eckhoff, & Breitner, 2023b). From this, the authors abstract the need for DSS' to depict location-specific data, languages, and currencies for international use. Multi-year simulations need to be implemented to account for volatility (Eckhoff et al., 2022; Hart et al., 2022).

Design Principle 4: Accessibility

The broad dissemination of existing DSS is often hindered by requirements for programming knowledge, specific operating systems, computers, high cost, and/ or language-specificity. Experts have expressed the need for mobile solutions and the necessity to cater to various cognitive and technological capabilities (Hart et al., 2022). Theories like Design for All and Universal Design Theory emphasize that the tool's design should aim for broad usability to improve the user's quality of life (Persson et al., 2015; Stephanidis, 2001). Therefore, a modern DSS should feature a user-focused interface, templates, expert settings, and assistive features like tooltips and user manuals. The system should be usable across devices and operating systems, cost-neutral, and reduce literacy and technological skill barriers (Robinson & Imran, 2015). The system's accessibility would be enhanced by language and currency options, and it should ideally be a free web-application with a graphical user interface. Given the prevalence of mobile phones in developing countries, the DSS should also be adaptable to all screen sizes.

Design Principle 5: Credibility

Expert interviews revealed that cost-neutrality could lead to stakeholder distrust due to concerns over data security and skepticism towards free products (Hart et al., 2022). Users may distrust DSSs from profit-driven companies due to potential bias in recommendations. Thus, it is argued that affiliation with a reputable non-profit organization can enhance the tool's credibility (Hart et al., 2022). The theory of Source Credibility suggests that a DSSs' credibility is influenced by the *perceived* expertise and trustworthiness of its source (Giffin, 1967; Hovland et al., 1953). Moreover, Wehmeier and Raaz (2012) find that transparency and openness about the source and the underlying calculations increase credibility. Thus, transparency about the source and the calculations used in the DSS is recommended, and prominently displaying sources, procedures, boundaries, and success stories from previous projects to foster a positive perception are suggested.

Design Principle 6: Tailored Complexity

The development of a DSS involved a constant balance between generating realistic results and maintaining user-friendliness (Eckhoff et al., 2023; Hart et al., 2022). The need for broad stakeholder involvement and comprehensive input fields for various technologies increases the system's complexity, knowledge requirements, and input times. Despite these challenges, limiting the DSS capabilities can lead to distorted results for certain stakeholders. While DSS cannot predict changing economic situations or completely reflect complex processes, they are still effective as first-decision support tools (Hart et al., 2022). To enhance user support, the DSS should provide automated features such as reference scenarios, data extraction, and individualized templates. For stakeholders requiring in-depth analyses, expert settings should be available. The design principles of the DSS should be bounded by factors like problem difficulty, stakeholder cognitive abilities, and time availability, aligned with the concept of Bounded Rationality (Selten, 1990; Simon, 1979). The system should aim for satisfactory rather than optimal decisions, adjusting to the stakeholder's motivation levels.

Design Principle 7: Uncertainty Representation

The planning process for sustainable societal transformation, particularly in renewable energy systems, is afflicted with uncertainties. To mitigate these, multi-year simulations considering demand changes, price volatilities, and component degradation are suggested following Fioriti et al. (2021). However, DSS are always subject to simplifications (see design principle Tailored Complexity) and cannot predict political, economic, and environmental uncertainties (Eckhoff et al., 2022). Validated by the Volatility-Uncertainty-Complexity-Ambiguity-World-concept, decision-makers need to base their decisions on incomplete or imperfect information (Mack & Khare, 2016). Thus, simulation models with various adjustable inputs and outputs for scenario creation and comparative analyses should be available. Within the framework of the Data-Information-Knowledge Pyramid, a DSS serves as a mechanism that facilitates the conversion of raw, observable data into meaningful information (Awad & Ghaziri, 2004). Nevertheless, individuals utilizing DSS are responsible of acquiring suitable information, comprehending its interconnections, patterns, and fundamental principles, along with the underlying problem being studied (knowledge), and to finally make a final decision considering uncertainties (wisdom) (Awad & Ghaziri, 2004).

Table 5: Design principles and features by Hart et al. (2024)

Design principle	**Grounding**	**Design features**
Comprehensiveness Enable a comprehensive analysis that considers the technological as well as the three sustainability dimensions.	SDGs (United Nations, 2015), Three Pillars of Sustainability (Purvis et al., 2019)	• Provide a multi-criteria DSS • Include all three dimensions of sustainability (economic, ecological, social) • Consider physical-technical inputs/ outputs and key performance indicators
Stakeholder involvement Identify stakeholders of the decision and ensure their participation and collaboration.	Participatory Action Research (Mumford, 1983)	• Provide a feedback form • Enable bottom-up decision support • Allow sharing of scenarios and inputs/ results • Visualize relevant key performance indicators
Location depictability Enable the consideration of site-specific characteristics and circumstances.	Contingency Theory (e.g., Gordon & Miller, 1976; Reinking, 2012)	• Include multiple currency options • Incorporate technologies common at site • Enable multiple language options • Cover location-specific data
Accessibility Ensure an accessible artifact for stakeholders of various capabilities and technological constraints.	Design for All (Persson et al., 2015)	• Develop a web-application • Ensure adaptability to all screen sizes • Provide the DSS cost neutrally • Include multiple languages • Ensure that no programming knowledge is required • Provide templates, tooltips, user manual, and expert settings
Credibility Convey credibility through a transparent artifact model and its boundaries.	Source Credibility Concept (Giffin, 1967; Hovland et al., 1953), Transparency Theory (Wehmeier & Raaz, 2012)	• Provide success stories and references • Provide company and affiliation information • Display developers' intention for DSS • Communicate simulation procedure and boundaries
Tailored complexity Create a simple, supporting artifact that provides explicit features for advanced analyses.	Bounded Rationality and Satisficing Concept (Simon, 1979)	• Enable advanced user settings • Provide different simulation modes and expert settings • Automate where possible • Incorporate pre-defined, adjustable data
Uncertainty representation Allow for the consideration of uncertain circumstances and developments.	VUCA World (e.g., Mack & Khare, 2016), DIKW Pyramid (Awad & Ghaziri, 2004)	• Consider future developments • Enable multiple simulation analyses for comparison • Allow simulation of component/ technology failures • Do not give specific recommendations for action • Enable depictability of stakeholder-specific cases

6 Discussion, Implications, Recommendations, and Limitations

6.1 Learnings for the Renewable Energy Transition in Developing Countries

The demonstrations, applicability checks, and case studies have shown that the goals of a long-term reliable, affordable, sustainable, and modern energy supply (i.e, SDG 7) requires the careful balance of technological capabilities and the three sustainability dimensions ecology, economy, and society. Indeed, NESSI's results demonstrated the ability of renewable energy systems to reduce pollution and improve energy security with particularly highlighting the advantage of storage-supported photovoltaic systems. Systems based on a diesel generator or the grid are often unfavorable in remote areas due to their environmental impact, high cost of refurbishment and extension, and dependence on fossil fuel (imports) - specifically in light of rising fossil and labor cost as well as dependency concerns. Further, the opposing forces of environmental sustainability and independence versus the economic attractiveness of a resilient renewable energy system were shown. Diesel generators, for instance, may ensure a reliable supply during demand peaks, uncertainties, and supply shocks. Including the social dimension may shift the favorability of various technologies. For instance, the often favorable storage-supported photovoltaic systems may inherit negative social characteristics due to its assumed relatively little local community and stakeholder impact in regard of investment, employment, and usability. Wind turbines, often considered too costly and ineffective, may socially be considered more advantageous due to, e.g., local production opportunities. The social benefits of diesel generators are elaborated on as their market including valuable local knowledge and acceptance in the Global South is well established. As it is found that particularly this dimension is highly dependent on user preferences and conceptions, these findings may vary significantly in other analyses. With the rapidly growing market of renewable energy technologies and corresponding innovations, certain social factors such as employment, usability, and local production opportunities may become more advantageous in the future.

In all studies, a strong influence of the availability, reliability, and price of electricity from the central grid was found. Stakeholders in countries with low electricity prices and high grid dependability may not be sufficiently incentivized to participate in the energy transition. Governmental subsidies toward renewable energy have proven supportive, however, they must be set carefully. High FITs may lead to low purchase rates of battery storage systems and high amounts of fed-in electricity which may result in grid overloads. Thus, FITs and electricity prices need to be carefully balanced. It is further found that the battery storage is a key technology toward an energy transition with focus on decentralized energy systems. Its sizing is prevalent in regard to the degree of self-sufficiency and self-consumption. Renewable energy technologies are indeed able to cover load demands. Nevertheless, due to their volatile output, the electricity is often produced at times not needed leading to the need to shift electricity. However, battery storage is often cost intensive resulting in energy systems that are economically not feasible. Innovation, the availability of rare earths, and developing supply chains may shift these results. Considering future developments, steadily rising prices of fossil fuels and reliance thereon due to increasing electricity demand are expected. Hence, GHG emissions and prices are anticipated to rise as well. Renewable energy technologies may support mitigating these developments and reducing the risk of energy-related poverty for vulnerable stakeholders. Due to their modularity, they may also account for future uncertainties such as unexpected demand changes and, thus, ensuring supply security. Further note that the articles included in this work have not touched upon further strategies toward the energy transition. Opportunities such as electric mobility and the thermal infrastructure is analyzable with the tool and should be subject of further research.

Generally, it is found that financial support through government incentives is needed. Without government subsidies even the most cost-effective decentralized renewable energy system is often more expensive than sole central grid supply or established conventional solutions such as the diesel generator. To guarantee the economic viability and profitability of renewable energy technologies, it is necessary to establish transparent and stable support systems that provide long-term assurance to investors, both during the initial investment phase and throughout operation. It was shown that carefully designed FITs and carbon credits are valuable means to encourage the uptake of renewable energy technologies. To overcome the initial investment barrier, energy policies that provide particular financial and technical support should further be implemented. One possibility is low-interest loans for small-scale photovoltaic systems and battery storage. Nevertheless, it is crucial to provide assistance to citizens in their pursuit of these grants and loans, given the potential limitations in their financial literacy. Reducing the cost of investment in renewable energy technologies is another way to alleviate investment challenges. However, the use of alternative technologies such as second-life batteries should be approached with caution. Their introduction needs to be preceded by the establishment of a legal framework that clarifies liability and the capacity of the product. Policymakers should consider the development of clear regulations as a long-term goal that businesses and industry can rely on over time. As highlighted in the results for the social dimension, it is further recommended to analyze local options when developing renewable energy systems. Local markets such as local manufacturers, operators, and maintenance companies may reduce transport and repair cost, promote entrepreneurship, create jobs, and encourage knowledge transfer. Specifically the latter is a strong influencing factor as it supports continued operation in the event of breakdowns and failures. As communities need to be involved in the decision-making process to ensure acceptance and long-term sustainability of the energy systems, tailor-made energy projects or better access to education programs are recommended. These findings are based on carefully researched input data. Nevertheless, it is again stressed that they base on inputs that may not suffice for specific settings or their foundation may already have or will change in the future. In order to formulate appropriate strategies and integrate the relevant energy systems, stakeholders are advised to conduct further analyses using this or similar methods. In conclusion, the choice toward a particular hybrid renewable energy system strongly depends on the users' knowledge, preferences, and conceptions as well as local conditions underlining the need for tailor-made energy transition strategies. Its complexity further calls for more intensive research, e.g., with DSS such as NESSI.

6.2 NESSI's Applicability

The applicability checks, case studies as well as user and expert feedback confirmed the suitability of the developed web-based tool for its intended application, i.e., decision support for planning renewable energy systems globally with a specific focus on circumstances in developing countries. Regarding the goal of supporting the SDGs, the tool enables solution-oriented investigations covering a comprehensive range of SDGs, specifically SDG 1 (no poverty), SDG 3 (health and well-being), SDG 11 (sustainable cities), SDG 13 (climate action), and SDG 7 (affordable and clean energy) as advocated by Leong et al. (2020), Gholami et al. (2016), and Walsham (2017).

The tool demonstrated robustness, practicality, and effectiveness. It meets most of the specified stakeholder-, model-, and system-centric requirements and strengthens the decision-making processes of a wide range of stakeholders. NESSI enables local stakeholders, including citizens, building and business owners, project managers, and energy consultants, to structure and systematically incorporate various key parameters into their decision process. For instance, NESSI allows to examine the impact and interplay of load shedding, price volatility, technology degradation rates, and shifts in energy demand, all of which are particularly relevant in the context in developing countries, negotiations with project investors and financiers, and relevant when deciding on technology and its sizing. The tool enables global use through simple map or coordinate-based location selection, automatic retrieval of worldwide specific weather data as well as various language and currency options. Its availability as a cost-neutral, accessible web-tool with built-in features such as RAMP, increases the stakeholders' accessibility to assess an energy system built for their individual needs and learn about the impact of their electricity usage behavior. The latter specifically increases the user's ability to assess the impact of purchasing additional appliances, increases environmental awareness, and highlights the impact of high-demand appliances. The tool enables behavioral changes in appliance use and can encourage activities that increase efficiency while reducing overall consumption. By providing stakeholders with insights into the intricacies of power system planning, NESSI promotes deeper engagement and strengthens ownership, leading to a more inclusive and effective path toward sustainable energy solutions. Additionally, the tool may be used as educational device enabling energy system literacy. Thus, by encouraging citizen participation in energy planning, the tool creates potential to create long-term successful project outcomes, as postulated by Urmee and Md (2016). Beyond this microcosmic context, NESSI supports policymakers to develop context-specific policies that are consistent with national and international sustainability goals. The tool provides an understanding of the impact of governmental policies and, thus, guides the formulation of tailored energy frameworks. Given the explicit inclination of governments to integrate information and communication technologies into energy planning, the research resonates with a wide range of stakeholders.

Nevertheless, it is essential to recognize that DSS, do not capture the complexities of reality. As inherent with simulation tools, assumptions which affect the results were underlined that may not be applicable to all cases. It is stressed that large parts of the tool are subject to simplifications which will distort results greatly. For instance, when considering the ecological impact of various technologies, only CO_2 emissions during operation are included without regarding life-cycle assessments and other polluting indicators are covered. Factors such as the grid's transmission losses, shading of photovoltaic modules, and thermal insulation, all of which have proven to have great impact on an energy system, are further not accounted for. Thus, the DSS provides the framework to transform technical, economic, social, and environmental data that can be transformed into information. The user or decision maker is responsible for sourcing this information, critically analyzing its relationships, patterns and principles, the underlying problem, and then making a final decision for their ideal energy system. It is encouraged that users critically evaluate and discuss the tool's inputs and results. User supervision continues to have a significant impact on the effectiveness and efficiency of the tool. Thus, although the software is designed to provide decision support for all, there is a vast amount and needed expertise for inputs and it is, thus, recommended to seek advice from knowledgeable users or experts.

6.3 Limitations and Challenges of Developing DSS

Several challenges that may limit the tool's applicability emerged during the development process. In the following four are highlighted, namely those pertinent to the instrument's credibility as an open-access tool, limited stakeholder cooperation and field testing, the overall identification of user groups, and the tool's complexity.

First, NESSI is presented as a modern web-based application that offers a high degree of accessibility and usability at no cost. However, due to data protection controversies and the platform's non-profit status may generate skepticism and reluctance among users, thereby, reducing their inclination to use it. It is found that for some stakeholders the tool's association with a research organization enhances its credibility. They also appreciate that the tool is not associated with companies that may pursue further interests. However, other stakeholders debated the trust of international actors in the tool. In order to effectively establish a solid foundation of credibility and trust, it is essential to build collaboration between local academics and practitioners, improve communication and training initiatives, and implement marketing strategies.

Second, one of the key issues in the development of this software is the lack of collaboration with local stakeholders as well as field testing. Working on-site allows for a more nuanced understanding of cultural, legal, and operational specificities. In this remote research, difficulties were encountered with data availability and quality, validation of assumptions, and utilization of the tool from local knowledge and requirements. Nevertheless, this remote research offered opportunities for efficiency, a streamlined development process, cost-effective collaboration, the use of diverse expertise, and avoided logistical problems specifically in light of Covid-19 travel restrictions. The use of advanced communication technologies further facilitated international collaboration and enabled the integration of a variety of perspectives. In addition, the remote development enabled the integration of global best practices. However, successful remote research requires a balanced approach to avoid mismatch between the simulator design and practical realities. Throughout the development process, the project team, therefore, worked virtually with stakeholders and companies globally to gather their feedback. Extensive user testing, expert interviews, academic reviews, virtual and on-site data collection, and (inter)national presentations were conducted. Moreover, to enable imputing individual knowledge and conditions, attention was paid to highly flexible energy system design options and to avoid clear recommendations for action provided by the tool. Nevertheless, face-to-face collaboration with local stakeholders who ideally take ownership of the tool could have enabled a more targeted development process. Such networks could have provided access to local projects allowing the tool to be used directly in practice rather than in fictive studies. The lack of real-time feedback on the functionality and usability of the simulator may have led to a discrepancy between the designed tool and the practical requirements. As the development team was based in Germany, this problem is particularly pronounced in research on global applications. It is, therefore, debatable whether the requirement to develop the instrument in close cooperation with potential stakeholders has been adequately met. Verification, validation, and beta testing in the field on real applications of NESSI is missing to date. Future research may further focus on building stakeholder relationships, collect more local feedback, and work closely with a broad range of potential users. It is recommended that the effective application of the tool for energy system project planning is not conducted remotely, but on site to ensure suitable input data and to take into account the unique characteristics and challenges of the energy infrastructure, political landscape, and socio-economic context of the target region.

Third, there are legitimate concerns about the impact of the broad definition of stakeholders on the complexity of the instrument. The more diverse this stakeholder group is defined, the more disparate the demands on the tool. The applied approach with numerous features is time-consuming in practice and its complexity may discourage certain user groups. There are also prerequisites for NESSI's use, such as educational level (e.g., literacy and numeracy), access to the Internet, and ownership of applications. Despite the extensive use of templates and tooltips, a user without broad technical understanding may not be able to utilize all features to gain the maximum benefit from the tool. For instance, if stakeholders do not use templates, information regarding toxicity and toxin level, efficiency of particular technologies, or supply security considerations may require specialized knowledge. Thus, knowledgeable individuals, educational institutions, non-governmental organizations, energy consultants, and policymakers are determined to be the most appropriate target group. These stakeholder groups may use the tool for the purposes of collaboration, interaction, and education with others. To reach the goal of providing a tool *for all* and empowering those involved during project planning, it may be necessary to offer special training.

Fourth, the level of granularity of the tool needed to be considered in each development step. Throughout the development process a high degree of specificity for realistic results and a high scope of possible applications was ensured. As a result, there was the constant challenge of balancing this target with the user-friendliness of the software. Using a sophisticated tool increases its adaptability and accuracy for planning sustainable energy systems. To accommodate the vast array of potential applications, numerous input fields, technologies, expert settings, and templates were provided. This increase in available options causes lengthier input times, necessitates a higher level of user proficiency, and ultimately contributes to a rise in complexity. Further, in light with the limited availability of (high quality) data in developing countries, inputs and outputs frequently exhibit ambiguity and subjectivity raising the question if such specificity provides the desired benefits. On the other hand, imposing limitations on the capabilities of the software diminishes its potential utility for the specified stakeholders. To reduce the complexity of the tool extensive support (e.g., customizable templates, help texts, tooltips) is, therefore, provided. However, using generalized inputs may produce biased results for specific users, necessitating the application of expert knowledge to identify and eliminate such biases. The tool functions as first decision support with its inherent nature as simulation tool with predefined assumptions in the calculation process, historic data (e.g., weather data), uncertainties, it will not be able to replace experts and energy consultants. To decrease complexities, each implemented indicator as well as additional features should be carefully evaluated in regard to their significance and necessity versus complexity and broad applicability in further research.

Interrelated with these challenges is the tool's comprehensiveness when it was released as web application. One of the interviewed experts drew parallels between other software development processes such as Instagram or Facebook. They noted that these applications began with very limited functionality and expanded over time based on user feedback. They outlined the advantages of releasing an imperfect instrument onto the market and allowing users to determine the primary areas of future development. In this case, NESSI was made accessible to the public when it was already quite comprehensive. This made certain modifications to NESSI's core difficult, despite being requested by users. It further complicated the instrument, causing some users to feel overwhelmed. This comprehensiveness was further challenged by the absence of a specific user group as this work instead focused on a broad user base. It is, therefore, recommended to start small with limited functionalities to release the product quickly, work closely with practitioners in the field, and put emphasis on user testing with a focus on a small stakeholder group. Consequently, it is essential to continue collecting user feedback and undertaking expert interviews in order to evaluate further the balance between complexity, applicability, realistic outcomes, and usability.

6.4 Further Comments

During the development of the tool, its related publications, and ultimately this dissertation, the term *developing countries* is used frequently. However, it is important to note that there is no agreed methodology or established practice to delineate between developed and developing countries. Categorizing countries oversimplifies the vast and diverse range of socio-economic conditions, diverse cultures, political systems, and various levels of technological and industrial development between and within a country. These terms may have a hierarchical implication and negative connotation for some readers. Nevertheless, it is still frequently used in the research world and international institutions, see, e.g., IEA et al. (2023), UNDP (2016), United Nations (2015). Internationally agreed goals such as the SDGs continue to use this term. This is possibly because it is well known, used for political and financial reasons, and perhaps also due to flexibilities resulting from its ambiguous definition. As this research is closely related to the SDGs and the term's frequent use in similar research, this work follows the IEA et al. (2023) and correspondingly continued to use the term. It is important to note that the authors acknowledge the controversies of this term and distant themselves from any negative connotation or hierarchical implication. In terms of the energy transition, it is rather used as a simplified demarcation to areas that are shaped by a stable, developed economic structure, and energy infrastructure. The term functions as a simplification to describe regions in which energy-related conditions are characterized by critical bottlenecks, are undergoing significant changes or are developing rapidly. Examples include traditional markets (e.g., widespread use of diesel generators), an underdeveloped or heavily burdened energy infrastructure (e.g., no prior access, overloaded power grids, power outages) and the impact on the energy system of rapidly changing economic markets (e.g., changing energy demand and technology prices, fast spread of innovative technologies). It is acknowledged that more specific and neutral terms should be discussed when going forward such as energy-transitioning countries, under-electrified/ energy-challenged regions or dynamic energy economies.

7 Further Research

NESSI offers an extensive research agenda which is divided into the three categories 1) software testing and evaluation, 2) research opportunities for the tool's status quo, and 3) possibilities that require extensive further adjustments. Despite this agenda, NESSI provides a valuable marketing platform for the institute and enables future cooperation with (inter-)national institutes, universities, and projects focusing on societal sustainability development.

7.1 Test and Evaluation Program

Although the tool was subject to feedback loops and user testing, extensive testing of each component's as well as the energy management's underlying calculations and assumptions to validate the tool's outputs is recommended. Following the development of other energy system simulators such as Hybrid2, this test program should include the three components verification, validation, and beta testing (Baring-Gould, 2022). First, the software's verification process should confirm that the source code accurately reflects the underlying mathematical algorithms. After already having conducted various verification checks on a fictitious scale, it is advised to add testing on various real energy system configurations. Second, during software validation, the predicted performance needs to be compared with measured performance data from working energy systems. Third, NESSI's beta testing should include testing by individuals outside the research team. In order to get feedback on the model's usability, efficacy, acceptability, and clear indication of limitations, a group of potential users from developing countries should be trained in its use and test the tool on real life cases. As mentioned above these qualitative testing can be enriched by further user surveys, interviews, and feedback loops. Quantitative measures for success and user satisfaction could include tracking the number of users, the duration of conducting simulations, and frequency of use. To determine the need for certain functions, developers could measure the percentage of users who click on and use these functions. Showing different versions could help to understand which features result in higher user satisfaction. Heatmaps, retention analyses, and benchmarking to other tools could further improve NESSI. Each step should carefully evaluate each component and feature in terms of its importance and necessity versus complexity and broad applicability.

In regard to the above-mentioned challenges during the development process three evaluation needs arose: First, further research may reevaluate the present stakeholder definition and analyze the possibility of offering multiple software tools that share similarities categorized according to user groups (such as experts, laypeople, and policymakers), geographical regions, electrical or thermal infrastructure, or population density. Thus, features not needed for the specific category may be eliminated leading to less complicated tools. Researchers should consider the need for communication between all stakeholders. Furthermore, stakeholder classification is challenging, and researchers need to ensure that users select the appropriate version for their application. Second, to reduce complexities, further research may evaluate the option to modularize NESSI to accommodate to the needs of the specific user group. This research direction, however, would entail that users are not able to immediately use the tool as preliminary discussions with the developers regarding the needed modules as well as programming time would prolong the simulation start. Third, future research may evaluate the option to switch from a ranking-based methodology to or add optimization, thereby reducing the number of required inputs. Optimization tools recommend targeted solutions, which means that they prescribe the user's needs and perspectives. Therefore, researchers need to allow users to prioritize and customize preferences given the subjective importance of each dimension and present positive as well as negative impacts of each recommendation. As the majority of optimization models have extensive computational times, it should further be evaluated if this option conflicts with system requirements and usability.

7.2 Research Opportunities for the Status Quo

Due to the tool's comprehensiveness, there are several opportunities for further research: Case studies exploring the opportunities of electric mobility and the thermal infrastructure in a hybrid energy system toward the energy transition may be explored. To further analyze the influence of location-specific characteristics, applications across regions and borders, in diverse ecological and economic settings as well as urban versus rural regions may shed light on their influence on energy systems and provide insights for policy formulation. The application checks and case studies conducted covered residential buildings and neighborhoods as well as guesthouses. To further evaluate opportunities for energy transition, NESSI is able to depict a wide range of building types, such as apartment buildings, commercial or educational buildings, or mixed neighborhoods, which may be subject to further research. Further research may also focus in-depth on each sustainability dimension: For economic factors, second-life technologies, governmental subsidies, investment opportunities, and the overall impact of technologies with differing quality and price ranges can be explored. Regarding the ecological dimension, life cycle cost, further pollution indicators, and waste management of each energy system combination offers great potential. As for the social dimension, the need to construct an improved framework and social sustainability score is highlighted. It is recommended to conduct interviews with various stakeholders and test the software specifically toward this dimension. To decrease complexities and enhance the tool's effectiveness, building a database of existing technologies that allows the user to pick and compare between and across components may be subject to further research. Hart et al. (2024) reflected and abstracted from the artifact and developed nascent design theory of societal sustainability DSS in developing countries. Further research may apply this approach to developed nations. The formulated design principles and features can further be applied to develop other DSS for societal sustainability transformation in developing countries and, thereby, validate the introduced nascent design theory. From the three levels of research contribution by Gregor and Hevner (2013), two are addressed in this work. Further research may continue this work by conducting research related to level 3, i.e., the development of theory based on the artifact and DSR approach.

7.3 Research Opportunities requiring Software Development

NESSI offers an excellent base for several research directions. There are various options to increase the level of detail for several technologies, such as shading for photovoltaic systems, transmission losses, and refined depiction of outages of the central power grid. Due to the vast amount and increasing number of conventional and renewable technologies, there is great opportunity to include other technologies into energy system simulators. So far, known technologies such as biomass, waste to energy as well as hydro and geothermal power plants have not been taken into account. Their application has been proven beneficial in developing countries and their inclusion into NESSI is, therefore, recommended. Moreover, including emerging technologies such as hydrogen, tidal wave energy or floating solar panels, provides opportunities in upcoming fields with great research gaps and needs. Each technology exists in various types: Wind turbines can be built with vertical or horizontal axis and photovoltaic systems are manufactured with different surfaces (thin-film, poly-, and mono-crystalline) each differing in efficiency, price, and robustness. It is also possible to explore different types of battery storage as this is a key technology for the energy transition. Further research may implement various electrochemical batteries, such as lead-acid, redox flow, sodium-sulfur, or zinc-bromine flow in addition to the lithium-ion battery implemented. Another option would be to analyze the opportunity of alternative technologies, such as thermal, thermochemical, flywheel, compressed air, pumped energy, or magnetic energy storage.

Next to opportunities of implementing various technologies, further research may focus on the risk assessment of hybrid energy systems. As such, features covering insurance opportunities and risks of natural catastrophes offer research opportunities which are especially prevalent for robust energy systems in developing countries. Last but not least an inclusion of of smart grid features such as emission and price trading between entities could be valuable. Tables 6 and 7 summarize the main research opportunities and give examples of research topics.

Table 6: Research agenda (1/2)

Research relating to NESSI's test program

- Testing an energy system simulation software: Validation, verification, and beta test of NESSI

Research relating to the energy transition of developing countries

- Fostering the energy transition through electric mobility: Exploring vehicle-2-grid opportunities in decentralized energy systems
- Opportunities of hybrid decentralized renewable energy systems in developing countries: Connecting the electric, heat, and cooling infrastructure in commercial buildings
- The impact of diverse environmental, economic, and social characteristics on energy systems of different regions in developing countries
- The impact of diverse environmental, economic, and social characteristics on energy systems across developing countries

Research focusing on the three sustainability dimensions

- Life cycle assessment of various technologies in hybrid renewable energy systems
- Beyond carbon dioxide: Carbon monoxide, unburned hydrocarbons, sulfur dioxide, nitrogen oxide emissions of renewable energy technologies in decentralized renewable energy systems
- A study of waste management of hybrid renewable energy systems in developing countries
- An updated framework to measure the social impact of hybrid energy systems in developing countries
- Opportunities and challenges of second-life batteries in developing countries
- Incentivizing stakeholders toward renewable energy systems through governmental subsidies
- The impacts of quality and price in renewable energy systems in developing countries

Research relating to risk assessments for energy systems in developing countries

- The role of insurance in hybrid renewable energy systems in developing countries
- Increasing the robustness of energy systems in developing countries against natural catastrophes

Research relating to theory building and application

- Developing societal sustainability DSS for developing countries: A waste management DSS
- Toward level 3: Design theory for DSS in developing countries

Table 7: Research agenda (2/2)

Research relating to the extension of NESSI

- Increasing usability through a database of real-world technologies
- Comparing various battery storage technologies in hybrid energy systems
- Impact assessment of hydrogen/hydro power plants/geothermal plants/tidal wave energy/floating solar energy in hybrid energy systems of developing countries
- Opportunities of alternative battery storage systems for renewable energy systems in developing countries
- Mitigating the impacts of power grid outages through decentralized energy systems in developing countries
- Opportunities and challenges of hydrogen in decentralized renewable energy systems in developing countries

Research relating to redeveloping NESSI's structure

- Defining stakeholder groups for energy system simulation software
- Introducing the optimization software $\mathrm{NESSI}_{\mathrm{Opt}}$
- Challenges and opportunities of modularizing DSS

8 Conclusions

Motivated by the calls for more solution-oriented studies that contribute to the energy transition, the open-access, web-based energy system simulator NESSI was further developed, evaluated, validated, applied, and abstracted for global use. Using an adapted design science research approach, NESSI was tailored in five consecutive design cycles specifically for actors in developing countries. For each cycle, objectives and requirements have been established through systematic market research, literature analyses, user tests, and expert interviews. After extensive iterative programming works, the tool was demonstrated, evaluated, and validated in and between each design cycle by applying it to a suitable context in developing countries to observe its ability to address the identified problem. The applicability checks were conducted for fictive residential and commercial buildings as well as neighborhoods in varying countries showcasing the tool's ability to consider local circumstances. Further methods to improve and validate the tool included reviewer feedback and presentation at national and international events. Two extensive case studies situated in Thailand and Colombia were conducted to further demonstrate NESSI. In order to improve input data, a GUI was built for the load profile generator RAMP and provided with a link to NESSI. Moreover, the functionality of the tool was introduced to support transparency, trust, and credibility and to highlight the tool's global applicability. Subsequently, nascent design theory was derived by formulating grounded design principles and features for the wider application of bottom-up societal sustainability transformation. It was highlighted that the software supports the bottom-up energy transition and with it the SDGs. Nevertheless, challenges during software development, specifically regarding the stakeholder definition, the remote research approach, the tool's complexity and credibility as well as missing stakeholder networks, are acknowledged. Thus, users must critically evaluate NESSI's inputs and results as any DSS presents a simplified version of reality. With an extensive research agenda, stakeholders and researchers are invited to further improve NESSI, challenge the approach, and together develop a more refined model to foster the bottom-up energy transition.

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A Appendices

A.1 Tool-based Renewable Energy System Planning Using Survey Data: A Case Study in Rural Vietnam

Authors: Maria C. G. Hart, Sarah Eckhoff, and Michael H. Breitner

Journal: Environment, Development, and Sustainability

Url: https://doi.org/10.1007/s10668-023-03120-4

Abstract: Renewable energies provide effective sustainable development by raising living standards, accelerating economic growth, and mitigating pollution. However, specifically in developing countries, the lack of information, data, and local expertise challenges the design process and long-term success of renewable energy systems. Following the call for inter-disciplinary, solution-oriented research, this work uses a design science research-approach to facilitate multi-energy planning. The decision support system NESSI4D is developed, which considers site-specific economic, environmental, technological, and social factors and is tuned for stakeholder needs in developing countries. Following a step-by-step process model manual, the artifacts applicability is demonstrated in a use case for a rural community in Thua Thien-Hue, Vietnam. Missing load data are synthesized from the TVSEP with the software RAMP. The results show that the implementation of renewable energy technologies only enables affordable, low-emission electrification with governmental financial incentives. Several sensitivity tests illustrate the impact of changing assumptions and highlight the importance of detailed analyses with highly specialized tools. The demonstrating use case validates the methods relevance for research and practice towards the goals of effective sustainable development.

Keywords: Sustainable Development Goals, Decision Support System, Renewable Energy Systems, Design Science Research, Vietnam, Load Profile.

A.2 Sustainable Energy System Planning in Developing Countries: A Decision Support System Considering Variations Over Time

Authors: Sarah Eckhoff, Maria C. G. Hart, and Michael H. Breitner

Conference: Proceedings of the 55th Hawaii International Conference on System Sciences, Virtual Conference

Url: http://hdl.handle.net/10125/79473

Abstract: Planning energy systems is subject to changes in components health and installation costs, fossil fuel prices, and load demand. Especially in developing countries, electrical loads are reported to increase drastically after electrification. Improper sizing of the energy systems components can lead to reduced environmental sustainability, decreased reliability, and long-term project failures. As no tools for energy system planning exist that aim at developing countries and sufficiently account for temporal variations, we modify the software NESSI4D in a design science cycle to provide the comprehensive decision support system NESSI4D^{+}. We conduct an applicability check with a representative rural village in mountainous Nepal that validates NESSI4D^{+}s relevance and shows the importance of considering temporal variations for economically, ecologically, and socially long-term sustainable energy projects.

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

A.3 Accessible Decision Support for Sustainable Energy Systems in Developing Countries

Authors: Maria C. G. Hart, Sarah Eckhoff, and Michael H. Breitner

Journal: Energy Informatics

Url: https://doi.org/10.1186/s42162-022-00255-y

Abstract: With rising electricity demand through digitization and innovation, the urgency of climate change mitigation, and the recent geopolitical crisis, stakeholders in developing countries face the complex task to build reliable, affordable, and low-emission energy systems. Information inaccessibility, data unavailability, and scarce local expertise are major challenges for planning and transitioning to decentralized solutions. Motivated by the calls for more solution-oriented research regarding sustainability, we design, develop, and evaluate the web-based decision support system NESSI4D$^{\text{web+}}$ that is tailored to the needs and capabilities of various stakeholders in developing countries. NESSI4D$^{\text{web+}}$ is open access and considers location-specific circumstances to facilitate multi-energy planning. Its applicability is demonstrated with a case study of a representative rural village in southern Madagascar and evaluated through seven interviews with experts and stakeholders. We show that NESSI4$^{\text{web+}}$ can support the achievement of the United Nations Sustainable Development Goals and enable the very prerequisite of digitization: reliable electrification.

Keywords: Web-based Decision Support System, Decentralized Energy System Simulation, Renewable Energy, Sustainable Development Goals, Design Science Research.

A.4 Sustainable Energy System Planning in Developing Countries: Facilitating Load Profile Generation in Energy System Simulations

Authors: Maria C. G. Hart, Sarah Eckhoff, and Michael H. Breitner

Conference: Proceedings of the 56th Hawaii International Conference on System Sciences, Hawaii, USA

Url: https://hdl.handle.net/10125/102726

Abstract: Successful energy system planning is dependent on detailed electricity demand information. Especially in developing countries, pre-generated load profiles are often unsuitable as appliance ownership and usage vary significantly across borders, between urban and rural areas, and on household and industry levels. Synthesizing load profiles is often hindered by the inaccessibility of tools due to cost barriers, global unavailability, or required technical knowledge. As currently, no easily accessible and usable tool is available during energy system planning in rural areas of developing countries, we incorporate the open-source load profile generator RAMP into our web-based energy system simulator NESSI4D$^{\text{web+}}$ to provide an intuitive user interface. We conduct an applicability check with self-collected data from a guesthouse in Sri Lanka, analyzing the impact of load distribution and magnitude on the economic, environmental, and reliable energy supply, that validates the artifact's relevance and ability to empower local decision-makers.

Keywords: Decision Support System, Developing Countries, Energy System Simulation, Load Profile Generation, Renewable Energy.

A.5 RAMP: Stochastic Simulation of User-driven Energy Demand Time Series

Authors: Francesco Lombardi, Pierre-François Duc, Mohammad A. Tahavori, Claudia Sanchez Solis, Sarah Eckhoff, Maria C. G. Hart, Francesco D. Sanvit; Gregory Ireland, Sergio L. Balderrama, Johann Kraft, Gokarna Dhungel, Sylvain Quoilin

Journal: The Journal of Open Source Software

Url: https://doi.org/10.21105/joss.06418

Abstract: The urgency of the energy transition is leading to a rapid evolution of energy system design worldwide. In areas with widespread energy infrastructure, existing electricity, heat and mobility networks are being re-designed for carbon neutrality and are increasingly interconnected. In areas where energy infrastructure is limited, instead, networks and systems are being rapidly expanded to ensure access to energy for all. And yet, re-designing and expanding energy systems in these directions requires information on future user behaviour and associated energy demand, which is often unavailable. In fact, historical data are either entirely missing or poorly representative of future behaviour within transitioning systems. This results in the reliance on inadequate demand data, which affect system design and its resilience to rapid behaviour evolution.

A.6 Threefold Sustainable Neighborhood Energy Systems: Depicting Social Criteria in Decision Support Systems

Authors: Maria C. G. Hart, Sarah Eckhoff, and Michael H. Breitner

Conference: Proceedings of the 29th Americas Conference on Information Systems (AMCIS) 2023, Panama City, Panama

Url: https://aisel.aisnet.org/amcis2023/sig_green/sig_green/6

Abstract: Despite the consensus that considering social factors is as important as economic and environmental dimensions for long-term successful, sustainable energy development projects, there is a lack of quantifiable assessments in multi-energy simulation decision support systems. Therefore, we applied a design science research approach to develop an energy system simulator that includes all three dimensions of sustainability. Based on a rigorous literature review and expert interviews, we establish a framework for assessing social sustainability. We then implement the derived criteria and indicators in the open-access software NESSI and validate it in an applicability check for a Madagasi neighborhood. With our framework, we aim to provide guidance to researchers and stakeholders on incorporating the social sustainability dimension into their approaches, tools, and decision-making process. The user-friendly, web-based simulation software enables various stakeholders to explore the interrelationships of threefold sustainability in specific energy systems.

Keywords: Social Sustainability, Multi-energy System Simulation, Decision Support System, Design Science Research, Sustainable Development Goals.

A.7 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

Journal: Building and Environment

Url: https://doi.org/10.1016/j.buildenv.2023.110296

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 multienergy 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 Hannover, Germany, and evaluated through twelve expert interviews.

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

A.8 Fostering Energy Resilience in the Rural Thai Power System - A Case Study in Nakhon Phanom

Authors: Maria C. G. Hart and Michael H. Breitner

Journal / Conference: Energies and TVSEP Conference, Goettingen

Url: https://doi.org/10.3390/en15197374

Abstract: With rising electricity demand, heavy reliance on imports, and recent economic downturns due to the negative impact of the COVID-19 pandemic, supply chain bottlenecks, and the Russian invasion of Ukraine, Thailand is suffering severely from energy resilience risks. The government has therefore set a goal of decentralizing energy production through small-scale distributed renewable energy systems. To support their design and the planning process, we simulate multiple scenarios with wind turbines, photovoltaic systems, and battery storage for a model community in rural Nakhon Phanom, Thailand. Using the software NESSI4D, we evaluate and discuss their impact on energy resilience by considering environmental sustainability, economic attractiveness, and independence from the central power grid. To fill the gap of missing data on energy demand, we synthesize high-resolution load profiles from the Thailand Vietnam Socio-Economic Panel. We conclude that distributed photovoltaic systems with additional battery storage are only suitable to promote energy resilience if the government provides appropriate financial incentives. Considering temporal variations and local conditions, as well as a participatory decision-making process, are crucial for the long-term success of energy projects. Our advice to decision-makers is to design policies and regulatory support that are aligned with the preferences and needs of target communities.

Keywords: Energy System Simulation, Energy Resilience, Distributed Renewable Energy, Case Study, Sustainable Development, Energy Policy.

A.9 Fostering Sustainability with Decentral Renewable Energy for Developing Countries: A Case Study in Colombia

Authors: Viktoria Redecker, Maria C. G. Hart, and Michael H. Breitner

Journal: Energy, Society and Sustainability

Status: Under review

Abstract: The energy transition towards a more sustainable, renewable energy production is a global aim. However, especially developing countries struggle with little information on renewable technologies and on suitable applications in local areas. We develop possible solutions to these challenges through data sourcing and provision of decision support within the scope of a case study in Colombia. Our approach consists of collecting data through surveys on household electricity demand in two cities in Colombia, generating corresponding load profiles, and calculating suitable renewable energy systems with the simulation software NESSI4D.We find that a promising solution for both locations is the expansion of the central grid with photovoltaic modules and battery storage as they provide noticeable economic and ecologic improvements combined with a higher degree of self-consumption and autarky. We recommend policy makers to support their implementation through feed-in tariffs as well as education in regards to renewable energy technologies with tools such as NESSI4D. Our contribution is threefold: First, we prove simulation software such as NESSI4D to be viable tools to educate and facilitate decision-making toward renewable energy systems and the broader goal of a more sustainable future bottom-up. Second, we close the gap of missing data and provide representative topical hourly load profiles for Colombian households to the research community. Third, we specifically provide recommendations for suitable renewable energy systems and supporting policies in Colombia.

Keywords: Energy System Simulation, Renewable Energy, Case Study, Colombia, Sustainable Development Goals.

A.10 Design Principles for Decision Support Systems Promoting Societal Sustainability Transformations in Developing Countries

Authors: Maria C. G. Hart, Sarah Eckhoff, and Michael H. Breitner

Journal: To be submitted

Abstract: Information systems have the potential to improve societal conditions in developing countries. To provide guidance to create decision support systems that foster societal change toward sustainability for developing countries, we derive design principles from reflection of a self-conducted development process. In five Design Science Research cycles we designed, developed, and evaluated a decision support system that promotes threefold (economic, ecological, and social) sustainable energy systems in developing countries through an open-access, free-of-charge web tool. Building upon the existing body of knowledge, our experience, and feedback from interviewees as well as local players, we deduce seven generalised design principles and accompanying design features. The design principles are grounded in kernel theories and address the wider application class of simulation software decision support systems that promote bottom-up societal sustainability transformations in developing countries. Our research process is framed according to Action Design Research. The design principles are 1. Comprehensiveness, 2. Stakeholder Involvement, 3. Location Depictability, 4. Accessibility, 5. Credibility, 6. Tailored Complexity, and 7. Uncertainty Representation and are enriched with three to six design features each.

Keywords: Nascent Design Theory, Decision Support Systems, Design Science Research, Sustainable Development Goals, Developing Countries.