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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

depicted in Figure 1: Five publications describe five design cycles of the tool's development process, i.e., Eckhoff et al. (2022) and Hart et al. (2022, 2023a, 2023b, 2023c). 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. (2023)), which has been integrated into the energy system simulator by Hart et al. (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).

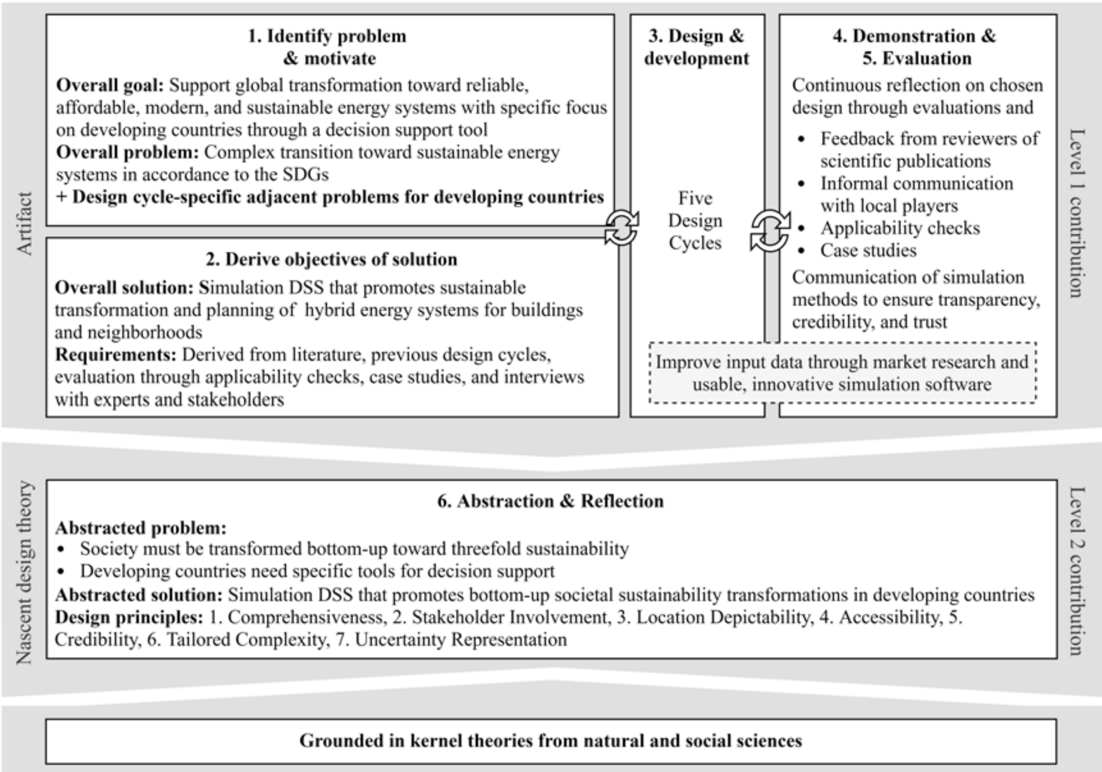

Figure 1: Overall DSR approach adapted from Hart et al. (2024)

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 et al. (2023c), 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 et al. (2023a) and Lombardi et al. (2023), and 5) the inclusion of the social dimension via a Social Sustainability Score, see Hart et al. (2023b)). 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 et al., 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. (2023)). 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 and Breitner (2022), Hart et al. (2022), and 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/.

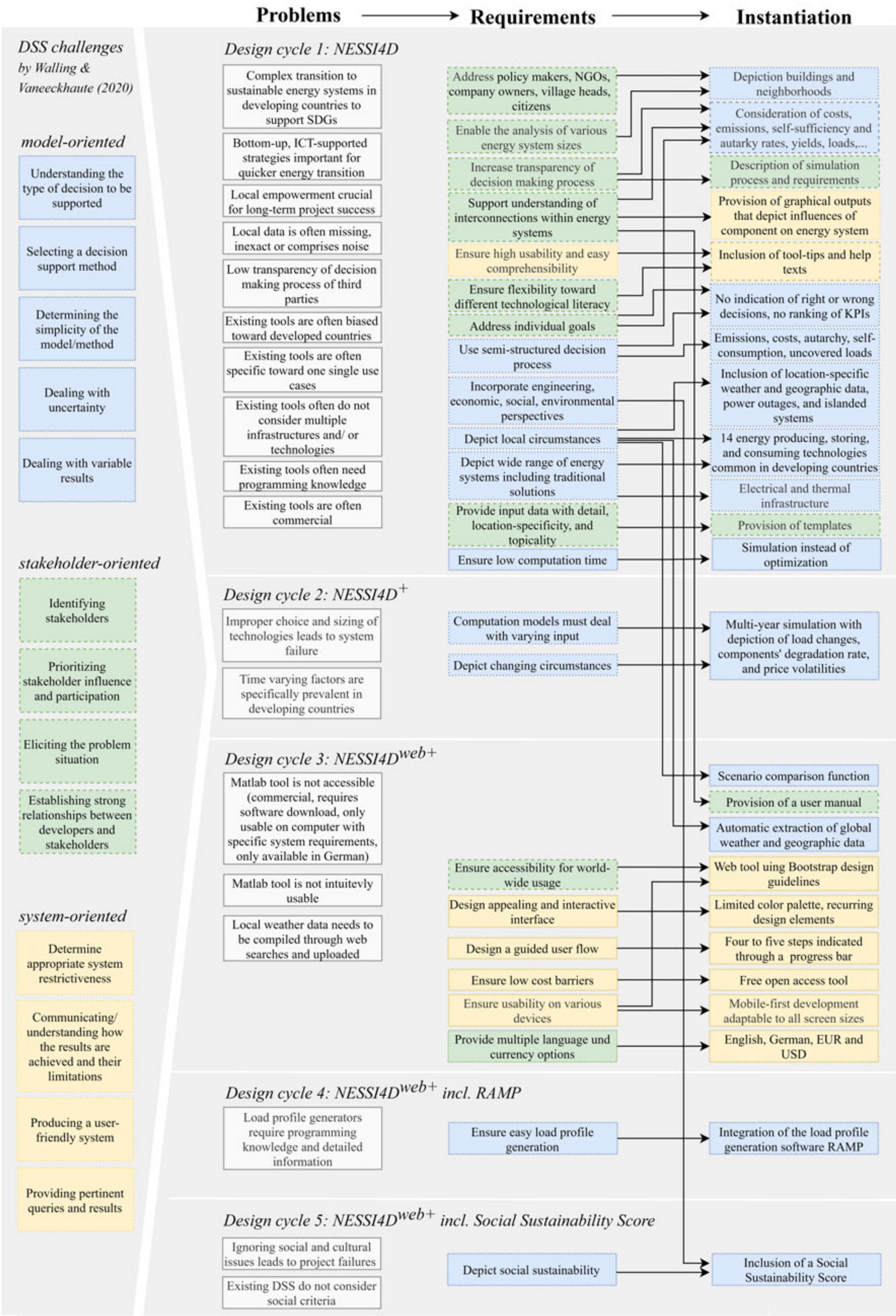

Figure 2: Problems, requirements, and instantiations of the design process adapted from Hart et al. (2024)

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 and Miller (1976) and 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 and 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.