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SOFTWARE

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Accessible decision support for sustainable energy systems in developing countries

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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*$^{web+}$ that is tailored to the needs and capabilities of various stakeholders in developing countries. *NESSI4D*$^{web+}$ 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 *NESSI4D*$^{web+}$ 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

Introduction

An electrical infrastructure is the prerequisite to use and benefit from digital technologies, and thus digitization itself (IEA 2017). It is estimated that up to 3.5 billion people still lack a reliable electricity supply and more than 700 million citizens have no access to electricity at all (Ayaburi et al. 2020). Without a reliable supply, they are unable to compete in today's fast-paced, globalized world, thereby being deprived of economic growth and human development (Ayaburi et al. 2020). The United Nations Sustainable Development Goals (SDGs), therefore, explicitly target global access to affordable, modern, reliable, and sustainable energy, see SDG 7 (United Nations 2015). Decentralized, hybrid fossil and renewable solutions for individual buildings up to entire neighborhoods play a key role in these efforts. These are not only capable of electrifying the most remote areas, but also strengthen reliability, increase resilience to future shocks, and support the energy transition towards a more sustainable future (IEA 2021). Due to fast population growth, increasing electricity demand, the urgency of climate change mitigation, and the recent geopolitical crisis, current efforts are deemed insufficient (IEA 2021). To accelerate and maximize societal impacts, international energy initiatives call for new electrification strategies, business ideas, and innovative technologies from both, top-down and bottom-up (IEA 2021). Thus, in addition to policymakers, building owners, businesses, researchers, and non-governmental organizations (NGOs) need to be empowered to tackle the SDGs individually. However, designing and transitioning to hybrid renewable energy systems (RESs) is challenging due to the complexities of energy components' characteristics, on-site conditions, and consumer-specific energy requirements (Al-falahi et al. 2017). In developing countries, economic barriers, lack of information, and inadequate energy policies often pose additional challenges towards electrification and the energy transition (Al-falahi et al. 2017). International energy programs have been incorporated globally, but often fail to include the citizens' needs and views. Social and cultural issues of target communities result in low acceptance leading to failures in the long term (Urmee and Md 2016). Therefore, stakeholders on site must be assisted appropriately in their decision processes towards an economically, socially, and ecologically sustainable energy system. Information and communication technologies (ICTs) provide new opportunities in this regard, especially in developing and transitioning countries (Walsham 2017). For these countries in particular, ICTs must become widely accessible, easy to use, and available at low prices to enable far reach and avoid cost as well as literacy barriers for users. There are several calls for more solution-oriented research in the Information Systems (IS) community and to address policymakers (Gholami et al. 2016; Leong et al. 2020). Our goal is to provide a freely available, easily accessible, and comprehensive decision support system (DSS) for stakeholders in developing countries to promote threefold sustainability in energy systems and ultimately positively affect societies. As accessibility to stakeholders is imperative, we consider the following research question:

How can stakeholders in developing countries be supported to sustainably build and transform local energy systems?

We conduct a design science research (DSR) process according to Peffers et al. (2008) to design and implement a web-based DSS specifically for stakeholders in developing countries that is freely available and easily usable. We build on the established and tested multi-energy DSS *NESSI* by Kraschewski et al. (2020). In addition to our solution-oriented, practical contribution, our research contributes to theory by providing a research tool to conduct in-depth case studies in developing countries. Our paper is structured according to Gregor and Hevner (2013). After a literature review, we present our "Research design and methods". The "Artifact description" consists of the set requirements, the design process and a demonstrating case study in rural Madagascar. We present the results of a comprehensive evaluation through interviews with experts and stakeholders in "Evaluation", before discussing its implications and limitations in "Discussion".

Literature review: theoretical background and related research

Green IS and energy for sustainable development

The United Nations defines sustainable development as meeting present needs without compromising the ability of future generations to meet their needs (Brundtland 1987).

Since this calls for improving and balancing economic, environmental, technological and social conditions for all, the UN has defined 17 SDGs (United Nations 2015). To reach these interrelated, often mutually exclusive goals, inter-disciplinary decision-making is required (Siksnelyte et al. 2018). Following these needs, the IS community also calls for research addressing sustainability as a core dimension (Seidel et al. 2017). Henkel and Kranz (2018) and Gholami et al. (2016) acknowledge global warming and environmental degradation as the world's most important challenges of our century and highlight information as a prerequisite for making appropriate decisions on the subject. Watson et al. (2010) postulate "Energy + Information > Energy" in the domain of Energy Informatics, implicating that information is needed to enable and support economic and behaviorally driven solutions. In Green IS, the demand for solution-oriented studies that use the "transformative power of IS to mitigate negative environmental impacts" is high (Gholami et al. 2016, p. 529). Despite its relevance, only a few research papers provide national or empirical insights for policymakers (Leong et al. 2020). There is also a call within the IS community to explicitly name the SDGs. Leong et al. (2020) found no papers addressing SDG 7 and only two papers addressing SDG 13 (climate action) in the AIS Senior Scholars' Basket of Eight journals. The transformative power of IS can play an especially important role in developing countries.

As economies increasingly rely on electricity, the energy sector plays a particularly important role for sustainable development, by improving living standards, enhancing international and national competitiveness, and transforming societies (UNDP 2016; Oliveira and Moutinho 2021). At the same time, the impacts of climate change, exacerbated by fossil fuel consumption, require a rapid energy transition, see SDG 7. Even though the energy situation worldwide has improved in the past decades, its stakeholders may be sensitive to supply shocks, price changes, and political frictions due to dependencies on primary sources (UNDP 2016). Electric power is also frequently unreliable, resulting in outages that negatively impact residential and commercial activities, lead to financial costs, and risk the environment's and the public's safety (United Nations 2022). Paired with the worldwide increased energy consumption driven by the growth of economies and human population, risks of energy shortages around the world arise (IEA 2021). In developing countries, this scarcity is often met with increased sourcing of fossil energy exacerbating the negative impacts on the environment and peoples' health. In order to successfully reach the SDGs, state and location-specific actions and policies must be undertaken (United Nations 2022). To ensure clean, reliable, and especially affordable energy for individuals, their demands, environmental settings, and supply options must be carefully evaluated. Stakeholders are often challenged by having to be knowledgeable about the energy components' functionality, geographic and weather conditions, and consumer-specific energy demands to implement suitable energy systems (Al-falahi et al. 2017). Information and data that need to be obtained from the real world are complex, comprise noise, are often incomplete and ambiguous (Cherni and Kalas 2010). Thus, stakeholders require support during the demanding energy planning process. This process differs in developing countries from that in the developed world, with many energy system models being biased toward industrialized countries (Debnath and Mourshed 2018; Urban et al. 2007). Al Irsyad et al. (2017) underpin the importance of adapting energy system analysis tools that are primarily designed for developed countries to location-specific circumstances. Deficiencies for energy planning models in developing countries include the lack of deliberation of low energy demand and socio-economic nuances (corruption and cost inflation), and shortcomings in data quality, availability, and adequacy (Debnath and Mourshed 2018). In addition, supply shortages, electrification, the poor performance of the power sector, traditional biofuels, the informal economy, and the urban–rural divide are often neglected (Urban et al. 2007). Cherni and Kalas (2010) highlight the importance of involving the local population in the decision process as their input, support, and investment are vital for successful projects. They state that additional factors for the failure of projects are inadequate technical information and lack of sustained financial resources that result in negative environmental impacts or drainage of scarce financial resources. Al Irsyad et al. (2017) call for a consideration of the four perspectives engineering, economic, social, and environmental when designing a DSS for developing countries. For the category of Environmental DSS, Walling and Vaneeckhaute (2020) collected stakeholder-, model-, and system-oriented challenges and how to overcome them when designing DSS. In addition, an evaluation criteria catalog is derived, stating that clearly defined evaluation criteria for DSS are lacking.

Related software

There are several papers about decision support web tools with an energy context. For instance, *Velix* is a tool motivating less energy consumption in Austria (Loock et al. 2013) and *The Green Fingerprint* supports sustainability-conscious behavior in the B2B setting (Ekman et al. 2015). Kontopoulos et al. (2016) designed an ontology-based decision support tool for the implementation of a suitable solar hot water system tailored for non-expert users and consumers. On a bigger scale, Irani et al. (2015) introduced the DSS *DAREED* to foster smart energy-efficient districts. Users are given recommendations to improve the buildings' energy efficiency with specific action plans including the economic parameters. These tools neither provide small-scale energy system simulations nor focus on developing countries. Outside the research community, there are also energy web tools. Model.energy computes the cost of covering electricity needs from combinations of wind energy, solar power, and battery storage (BS) (Brown et al. 2022). Shortcomings are the consideration of only a constant electricity demand and the limited possibility to switch between different currencies. *En-ROADS* visualizes global energy scenarios and includes policies and future growth (Climate Interactive Revision 2022). It cannot be used to make individual, small-scale decisions on the building or neighborhood level. Further, a vast amount of expert energy system analysis tools without a web interface exist, see Mahmud et al. (2018), Tozzi et al. (2017), and al Irsyad et al. (2017). Widely-known tools are *HOMER*, *iHoga,* or *Hybrid2* which conduct comprehensive techno-economic optimizations determining optimal sizing of components and minimizing net cost (Sinha and Chandel 2014). They have successfully been employed for case studies covering developing countries (Sinha and Chandel 2014). Energy system analysis tools mostly require expert knowledge and often apply optimization algorithms that need high amounts of computing power and time. In addition, their often commercial nature prevents stakeholders from using them. We found one DSS especially for developing countries: *SURE-DSS* by Cherni and Kalas (2010) uses a people-centered

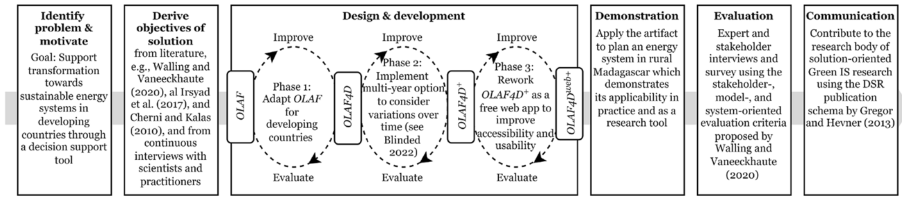

Fig. 1 Research design. Adapted from Peffers et al. (2008)

sustainable livelihood approach to plan the electrification of remote regions but it is not an energy system simulator. In summary, existing web tools do not offer the desired functionality of designing energy systems for rural buildings and neighborhoods in developing countries. Furthermore, common energy system analysis tools are not easy to use or accessible for stakeholders in developing countries.

Research design and methods

Our research question addresses the situated implementation of an artifact (Gregor and Hevner 2013) which justifies the use of the DSR method. We adapted the DSR approach of Peffers et al. (2008) for our needs (see Fig. 1) and follow the DSR publication schema proposed by Gregor and Hevner (2013). We approached the problem of accessible decision support for stakeholders in developing countries in several iterations. We report on the final improvements of the artifact and present it as the result of an overarching design science process as shown in Fig. 1.

After formulating the problem (see "Introduction"), we derived objectives and requirements for our tool from literature (see “Artifact description”). In the design and development process, we used the decision support tool *NESSI* (Kraschewski et al. 2020), which addresses stakeholders in developed countries, as a starting point. We reported on the second iteration of the software in Eckhoff et al. (2022). The last iteration, which focuses on improving the accessibility, and the finished artifact are subject of this work and are presented in “Artifact description” . Afterward, we demonstrate the user’s interaction with our artifact with an exemplary case study set in Madagascar. Lastly, we conduct a comprehensive evaluation of our artifact by conducting expert and stakeholder interviews, see Table 1. In our case, the delimitation between expert and stakeholder is blurred as energy experts in NGOs and companies are one of our artifact’s addressees. We follow Walling and Vaneeckhaute (2020) and structure our DSS evaluation in stakeholder-, model-, and system-oriented criteria. The evaluation interviews were conducted semi-structured, lasted 60 to 90 min, and took place in March and April 2022. The interviews started with introductions of each participant. Then, the authors shortly gave context to the problem the artifact alleviates, followed by an in-depth presentation of *NESSI*’s functionalities with an example use case. Afterward, the participants were asked the following open questions to initiate a discussion: (1) Do you have general questions about *NESSI*? (2) How do you rate *NESSI*’s benefits for stakeholders in developing countries? (3) Do you have any suggestions for improving *NESSI*?. As a follow-up, we prepared questions regarding each evaluation criterion that were asked if the topic was not raised in the discussion. Supplementary, we asked each participant to fill out a survey after the interview that queried each criterion on a 5-point Likert scale and offered additional text fields to allow anonymous comments with the benefit of hindsight.

Artifact description

Objectives and requirements

To establish a systematic artifact design and development, we follow Walling and Vaneeckhaute's (2020) categorization of stakeholder-oriented, model-oriented, and system-oriented challenges and derive our DSS' requirements. Regarding the first category, we aim to promote sustainable, affordable, and reliable energy systems in developing countries to provide positive drivers for the SDGs, local empowerment, and digitization. The planning process of energy systems is complex and requires the inclusion and understanding of social, economic, technical, and environmental aspects that have considerable uncertainties and interrelationships. Thus, the service our software will provide is decision support. We use Power's (2008) definition of a DSS as an "interactive computer-based system or subsystem intended to help decision-makers use communication technologies, data, documents, knowledge, and/or models to identify and solve problems, complete decision process tasks, and make decisions" (p. 149). Declared as the DSS' inherent characteristics by Walling and Vaneeckhaute (2020), we also aim to increase transparency, enhance the approachability to renewable energies, and support the understanding of interconnections within energy systems. For maximum societal impact, our initial stakeholder definition includes policymakers, NGOs, company owners, and citizens in the context of developing countries. The software must be usable and easily understandable, flexible towards the different technological literacy, and address their individual goals and needs to ensure the participation of all stakeholders to enhance the prospect of the projects' success. Regarding the model-oriented requirements, we consider the complex decision process as semi-structured, i.e., the decision formulation can be specified and structured, while the decision solution depends subjectively on the preferences of the decision-maker (Walling and Vaneeckhaute 2020). We use simulation models that enable the creation of different energy system scenarios with varying inputs, allowing to tackle the challenges of uncertainties and variable outcomes while planning energy systems (Walling and Vaneeckhaute 2020). As called for by al Irsyad et al. (2017), our DSS must provide the four perspectives engineering, economic, social, and environmental and, thus, function as a multi-criteria system whose benefits are often highlighted in the literature (Cherni and Kalas 2010). Tackling the challenges of energy planning in developing countries, it must consider local circumstances, including location-specific weather and environmental conditions, individual load profiles, performance characteristics of the power sector, and available financial resources. Several energy-producing, consuming, and storing components must be available to compare a wide range of energy systems. Not only the electrical but also the thermal infrastructure must be included to increase efficiency. Further, comparisons to traditional solutions such as grid connections or fossil fuels must be available. The DSS must encompass buildings and neighborhoods to facilitate analyses on multiple levels and of all stakeholders. Prevalent for the transforming energy sector and the fast-changing activities in developing countries, variations over time must be further considered to allow for successful projects in the long term. Following Leong et al. (2020), our DSS addresses

Table 1 Evaluation interviews participants overview

Participant no.	Category	Job description	Experience in
Participant 1	NGO	Consultant for Development Works	Indonesia, Serbia, Yemen, Bosnia and Herzegovina
Participant 2	Business	Consultant for Construction Projects	China, Azerbaijan, India, Bahrain, Malaysia, Russia, Brazil, Morocco, Kazakhstan, Oman, Kenya, Mexico, Turkey, Viet Nam
Participant 3	NGO/ Academia	Head of Division Science and Technology/ Project Manager	Indonesia
Participant 4	Business	Founder & CEO of a Renewable Start-Up	India
Participant 5	NGO/ Business	Consultant/Founder & CEO of a Renewable Start-Up	India
Participant 6	Academia	Researcher in Development Economics	Tanzania, Cambodia, Namibia, Thailand, Viet Nam
Participant 7	Academia	Senior Researcher in Electrical Engineering	Bangladesh, Ghana, Namibia, China

mainly SDG 7, but also SDGs 11 (sustainable cities and communities), and 13 (climate action) and consequently needs to include key variables that infer the system's greenhouse gas (GHG) emissions, reliability, and feasibility. Throughout the design process, the efficiency and quality of the model must be carefully weighed, as severe simplifications can lead to unrealistic outcomes, while complex models can overwhelm users (Walling and Vaneeckhaute 2020). With regards to system-oriented requirements, pertinence, appropriate restrictiveness, and high usability must be ensured with an appealing and interactive design, guided user flow, and low computation time. Specifically, for the research in developing countries, the tool must be readily accessible for worldwide usage to raise awareness of renewable energies and support their implementation. This includes low-cost barriers, its usability on various devices, and multiple language and currency choices.

Design and development

We based our DSS on the energy system simulator *NESSI*, which meets our base requirements. Following Peffers et al. (2008), we have improved the software in several iterations to meet the needs of stakeholders and consider the unique circumstances when planning energy systems in developing countries. We gave the resulting prototypes unique names to ease the academic communication but still refer to the overall tool as *NESSI* to stakeholders. Each phase was independently evaluated with peer-reviews, conference discussions, and feedback from business and scientific presentations. The resulting recommendations were evaluated by the project team and implemented as applicable.

The Basis: NESSI

NESSI is an energy system simulator in *MATLAB App Designer* that simulates thermal and electrical energy flows in hourly time steps over one year, calculates total costs in Euro, and computes GHG emissions (Kraschewski et al. 2020). The user can choose photovoltaic (PV) and solar thermal systems, heat pumps, hot water storage, BS, combined heat and power systems, gas boilers, connections to a central power grid, and local heating as well as battery-electric and internal combustion engine cars. Location-specific temperature and solar radiation time series were collected from the NASA Merra-2 dataset. *NESSI* considers capacities, efficiency rates, feed-in tariffs, component and fuel prices, as well as GHG emission factors and checks user input for technical feasibility and plausibility. In pre-processing, solar yields of the PV and solar thermal systems and the coefficient of performance of the heat pump are computed. In addition, the space heating load is derived from the building size, insulation, and air temperature. Subsequently, the simulation and economic analyses are conducted. The energy management is based on a reliable ranking method. Total costs are calculated based on the annuity method to get a fixed annualized value that comprises the discounted initial investments, operation, management, and demand-related costs as well as the generated yields from selling surplus energy (Kraschewski et al. 2020). In summary, *NESSI* meets our requirements to offer decision support through simulation models, meet economic, ecological, and technical objectives, and function as a multi-criteria system. We, therefore, chose this tool as our basis for further developments.

Phase 1: focus on developing countries: NESSI4D

To meet existing energy market structures in developing countries, increase flexibility and the system's robustness, we expanded the electric infrastructure with new energy-generating technologies, such as a small-scale wind turbine (WT) and fuel-based generator. In light of recent developments in electro-mobility, power generation, and cost advantages of electric two-wheelers in developing countries with high reliance on fuel imports, we enabled the simulation of battery as well as fuel-powered light motorcycles. We also enabled the modeling of power system expansions and potential outages, to increase the modeling accuracy of potential circumstances in developing countries. When excess electrical power cannot be used or stored, it is discharged in a reactive load such as a simple immersion heater. Thus, excess electrical energy can be used to heat a body of water for washing or showering. Economic calculations were improved by introducing US Dollars (USD) as a further currency option as it is commonly used when planning energy systems in developing countries. Particularly in developing countries, microgrids provide an opportunity for electrification in remote areas where grid expansion is economically or technically infeasible (Cagnano et al. 2020). Additionally, they support the integration of distributed energy sources and reduce losses through shorter transmission distances (Saritha et al. 2016; Cagnano et al. 2020). Thus, we created the possibility to combine the results of the building analysis to study neighborhoods and villages as microgrids. A high level of detail and flexibility is achieved by merging the results after simulating the individual houses. To tackle the challenge of missing energy demand data, we provide load profiles from detailed household survey data pre-generated with the software RAMP by Lombardi et al. (2019). Alternatively, self-generated load profiles can be imported. In summary, we met our requirements of expanding the model of the software towards the unique energy system circumstances in developing countries, including new energy-producing, -consuming, and -storing components, and enabling the simulation of neighborhoods. We validated and cyclically improved our software through an extensive applicability check and various sensitivity analyses in rural Vietnam and Thailand, see, e.g., Hart and Breitner (2022).

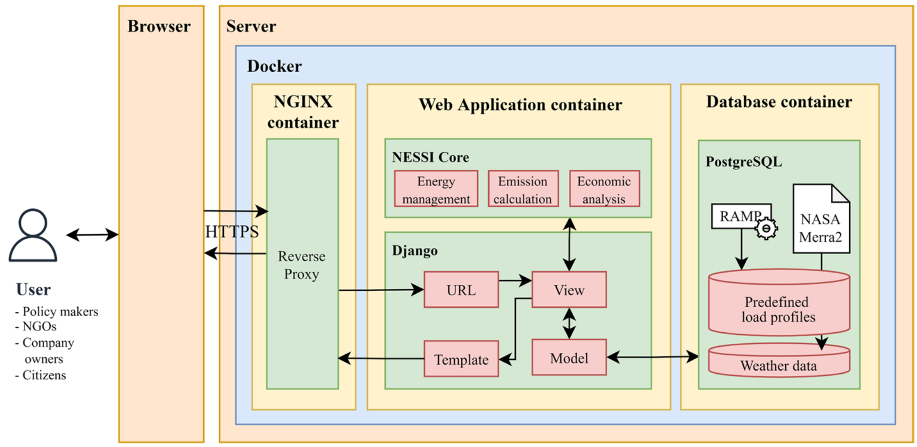

Fig. 2 Software architecture of NESSI4D^{web+}

Phase 2: focus on uncertainties: NESSI4D^{+}

Walling and Vaneeckhaute (2020) highlight the importance of considering uncertainties in Environmental DSS. We followed their recommendations by choosing a DSS with simulation models and validating our simulation results with sensitivity analyses. After thorough literature reviews and various case study findings regarding energy system planning, we found that further considerations towards uncertainties are necessary. Specifically, the fast-changing settings in developing countries increase the need to include time-varying factors (Fioriti et al. 2021). Thus, we implemented the option to include demand changes, price volatilities, and component degradation. We validated its impacts and importance for developing countries with a case study situated in rural Nepal and evaluations through peer-reviews and conference discussions (Eckhoff et al. 2022).

Phase 3: focus on accessibility: NESSI4Dweb^{+}

As stated above, we have found that existing modeling tools do not fulfill the requirements of usability and worldwide accessibility in developing countries due to monetary, knowledge, or technological constraints for stakeholders. For our purpose of supporting the implementation of affordable, reliable, and modern energy systems, fulfilling these requirements is crucial. However, *NESSI* was developed with the commercial software *MATLAB App Designer*, making access for all stakeholders difficult and constraining design options. To provide easier access and account for circumstances in developing countries, we switched to the open-source programming language Python (v3.8) and provide *NESSI* as a web tool free of charge. We chose *Django* (v3.1.6) as it is a state-of-the-art web framework and database *PostgreSQL* 13. The back end is dockerized to provide easy portability and further development on all devices. The server runs on Linux distribution Debian 10. The implementation as a web tool allows the development of a high-quality, modern, and interactive graphical user interface. It further increased accessibility as the interface is adaptable to all screen sizes, avoiding the dependency on a computer for the use of the software. The resulting software architecture is depicted in Fig. 2. The website is available at https://nessi.iwi.uni-hannover.de/en. We further provide a manual, guide the user in five steps through the simulation, and include help texts for each input and result variable. We offer templates with predefined parameters for component settings based on verified literature, but parameters can be adjusted at any time. The templates can be used with both currencies. The corresponding conversion factors are stored in the database and updated periodically. To meet the different levels of literacy regarding energy system planning, we added expert settings, provide the option of viewing results at different levels of detail, and allow to download results in Excel format for further analyses. To save, compare, and share simulations, we enable the creation of individual user accounts and a summarizing dashboard. We meet the requirement of location-specific weather data as the software retrieves worldwide and location-specific weather data from the NASA Merra-2 dataset that has a resolution of $0.625^{\circ} \times 0.5^{\circ}$. Lastly, following the recommendations of expert discussions, we reworked the neighborhood simulation. In its prior phase, the buildings were individually simulated and subsequently added to a neighborhood. As required, we carefully weighed the efficiency and quality of the model and decided to ease the user flow. Now, neighborhoods are modeled in an aggregated way using one simulation process instead of having to simulate individual buildings first. Components are defined neighborhood-wide while load profiles are defined on a per-building respectively a per-building-type basis. During the simulation, all loads are aggregated and treated as one neighborhood load. This allows for faster result generation at the cost of losing levels of detail. A feedback button is added to allow continuous improvements.

Demonstration

To demonstrate how users can interact with *NESSI4D*$^{web+}$, we conduct an exemplary case study set in Madagascar. We first assessed the current energy-related conditions and goals in the analyzed country. From these findings, we constructed various realistic energy system scenarios to compare their suitability with respect to the derived objectives. We collected detailed, literature-based input data and generated survey-based load profiles. After explaining all corresponding steps in our software, we present, discuss, and interpret the simulation results in an aggregated manner to illustrate the wide range of opportunities for data-based (policy) implications.

Problem formulation, input data, and NESSI4Dweb^{+} flow

Only 13% of the Malagasy population is electrified and most rely on low-quality energy sources that are inefficient and lead to environmental damage and health risks (Surroop and Raghoo 2018; Nematchoua et al. 2021). The unaffordable electricity cost prevents businesses from becoming competitive and households from raising their standard of living (Nematchoua et al. 2021). Reliance on fossil fuel imports threatens the country's energy security through supply and price shocks (Surroop and Raghoo 2018). Thus, several national and international initiatives aim to improve the energy situation with a strong focus on renewable solutions (Garcia and Raji 2020). We, thus, focus on electrification and basic electric demand. Our objective is to compare the options of expanding

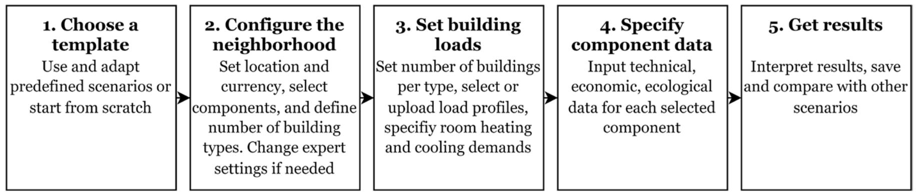

Fig. 3 User flow of *NESSI4D*$^{web+}$*s* neighborhood simulation

the national power grid with an island microgrid powered by a diesel generator (DG) or renewable energy technologies (RETs) in light of reliability as well as economic and environmental sustainability.

The user flow for a neighborhood simulation is depicted in Fig. 3. To start the simulation, we open the website on our laptop. Alternatively, we could use a smartphone or any other device with internet access. The graphical user interface guides us through the application starting from a general explanation of the tool and user manual. Firstly, we choose the language English. We then create an account to enable comparing various scenarios and sending the results to colleagues. We are given the option of either simulating a single building or a neighborhood. For our applicability check, we aim at constructing a representative village and, thus, select the neighborhood simulation. We now follow five simulation steps: The first step *Templates*, offers the options of choosing a template with pre-defined data or starting from scratch—due to the unique simulation problem, we choose the latter. In the subsequent step *Neighborhood*, we input general neighborhood data: on the world map, we set the marker on a rural area near Ambovombe located in the South of Madagascar and select the currency USD. We then choose components for the neighborhood. In our first scenario, we include a locally producible WT, as the use of local materials promises positive social impacts. Further, we select PVs, because they are considered the main solution to improve rural electricity in Madagascar (Praene et al. 2017). We use second-life batteries to increase the energy system's efficiency while respecting local financial constraints. Due to the households' low income, we limit the supply of hot water to what is produced from excess electrical energy and omit the possibility of air conditioning. As the average daily temperature does not fall below the threshold of 15 °C at any time of the year 2019 in Ambovombe, we assume no heating demand. We thus, omit the thermal infrastructure and consequently do not choose corresponding components. We aim to simulate a representative village that comprises 30 households of equally the low and lower-middle-income group, an administration office, and a school. Therefore, we input four different building types. In the expert settings, we assume a 20-year project length, select an interest rate of 6% (The World Bank 2019), insert expenditures for the installment and operation of an island power grid as detailed in Table 2, and leave the other expert settings unchanged (hot water temperature, daily mean temperature threshold for space cooling, and CO_2-tax) as we only consider the electrical infrastructure without governmental incentives. For simplicity, we also omit the option for multi-year simulations (for a demonstrating case study of this feature see Eckhoff et al. (2022)). We are guided to the *Building* tab, where we input load profiles for each building and household type that we generated with the software RAMP (Lombardi et al. 2019) with information from household survey data by Enclude (2018). Since we have omitted the thermal infrastructures, we indicate not to calculate the space heating and cooling demand. In the last input step *Components*, we specify detailed technical settings, investments, and operation and management (O&M) costs as summarized in Table 2. We then start the simulation. After an approximate computation time of 3 s, the results are presented with key indicators and temporal graphs in the fifth step, the *Results*. We see several tabs including a general overview (e.g. total cost, local emissions, degree of autarchy and self-consumption, uncovered loads), component-specific outcomes (e.g. O&M costs, feed-in revenue, energy yield), and load profile information, that present the scenario's outcomes at different levels of detail. For a definition and further information on the key variable degree of autarchy, we click on the small question mark that is found next to almost all input and output variables. In the expert functions, we download the results as an Excel file for further analyses. As we want to compare different energy system scenarios, we save our results and go back to the second step (*Neighborhood*) via the progress bar to choose different energy technology mixes and include further components, e.g., a back-up DG or central power grid (CPG). In total, we simulate 11 different scenarios. In the dashboard, we find all saved scenarios, compare them for a detailed analysis, and share all scenarios with our colleagues by creating individual links.

Results, scenario comparison, and findings

The village's total electrical load sums to 880 kWh/a. With the local weather conditions and selected settings, the WT generates 5198 kWh/a and PV 1927 kWh/a. The DG yield depends on its use and ranges from 161 kWh/a (WT-PV-DG) to 2715 kWh/a (DG). The surplus energy can be converted to hot water with an immersion heater resulting in up to 6.6 l per building and day. The degree of autarchy ranges from 48% (PV) to 95% (PV-WT), and increases to 100% when a DG or BS is added.

Figure 4 presents our three objectives economic feasibility, environmental sustainability, and system reliability in a consolidated form. RESs with an optional BS are the most economical and ecological solutions. The annual cost of these RES ranges from 837 USD (PV-BS) to 1064 USD (PV-WT-BS), while solutions with DG cost between 1159 USD/a (WT-PV-DG) and 1818 USD/a (DG). The DG costs are driven by its fuel consumption and minimum load ratio. Driven by the infrastructural changes, the highest cost occurs when all households are connected to the central grid (2901 USD/a). While energy systems only powered by RETs do not generate GHG emissions during operation, solutions with an additional DG emit between 165 $kg_{CO2\text{-}eq.}$/a (WT-PV-DG) and 1483 $kg_{CO2\text{-}eq.}$/a (PV-DG). These values depend strongly on the run-time of the DG which is correlated to the RETs' generated electric energy available at that hour. Thus, without adding RETs to a DG-powered system the most GHG is emitted (2788 $kg_{CO2\text{-}eq.}$/a). Regarding the energy system's reliability, full load coverage can be achieved by RETs with additional BS or additional DG or connections to the national grid. However, the latter two solutions are associated with higher costs and GHG emissions. In summary, the combinations PV-BS, WT-BS, and PV-WT-BS show high potential to provide economical, ecological, and reliable electricity for the representative village in Ambovombe.

Implications

We find that RESs are environmentally advantageous over traditional solutions for our case. Grid expansions and the inclusion of DGs increase direct as well as indirect GHG emissions and, thus, the ecological footprint of energy systems. As energy demand is expected to increase, more fossil fuel imports and mining can be expected in Madagascar in the future. We are able to quantify and illustrate these negative trends and simultaneously showcase the positive impacts of renewable energies. Economically, we observe similar outcomes. However, the households' income does not surpass the value of 12 USD/month (Enclude 2018). Even the most economical RES (PV-BS) requires village-wide investments of 7925 USD, which is 3605 USD higher than the village's yearly income. Thus, when putting these results into the local context, we may reflect upon appropriate energy policies such as subsidies or feed-in tariffs to support the RETs' implementation. Selling surplus energy could have a positive impact on overall access, encourage investments, and increase household incomes. Regarding the dimensions reliability and independence, *NESSI4D*$^{web+}$'s results demonstrate that it is indeed possible to foster these aims with RETs. Moreover, the software illustrates which technologies are most effective. To meet socially relevant factors, *NESSI4D*$^{web+}$ allows high flexibility regarding its input data. We were able to simulate non-commercial RETs, i.e. a locally producible WT and second-life BS. The former may add local value through on-site business opportunities for the distribution, installation, and repair of WTs. These create job opportunities, encourage entrepreneurship, and enable knowledge transfer. Second-life batteries have been regularly used as an alternative power source for rural households in Madagascar (Cholez and Trompette 2020). This indicates their local availability and facilitating rural acceptance, which are two crucial factors for the long term success of energy systems. Thus, we find that the needed dimensions to reach our aims for the Malagasy energy market can be reflected with *NESSI4D*$^{web+}$. With the gained insights about the interrelations of the energy technologies, we may be encouraged to conduct further studies with *NESSI4D*$^{web+}$ to quantify the impacts of rising energy demands, increased fossil fuel consumption, and governmental policies at different sites to transform the Malagasy energy system and impact the society positively.

Evaluation

After demonstrating that the artifact can provide useful information for supporting decisions toward independent and sustainable energy systems, the last step in our DSR cycle is to evaluate *NESSI4D*$^{web+}$ (Peffers et al. 2008). Regarding the ultimate goals of our tool, Participants 1, 2, and 6 highlighted the software's benefits for independent, educated decision-making in the investment process and confirmed the utility of the software for demonstrating energy-saving opportunities and for educational purposes. Ultimately, Participants 4 and 5 highlighted the importance of democratizing renewable energy, i.e. enabling and empowering people towards their usage, for maximum impact on the SDGs and energy dependence, and strengthened the efficacy of our tool towards these goals. Several participants offered to disseminate the software in their network, connect us with potential cooperation partners, or consider it in future research projects. We received positive feedback regarding all evaluation dimensions, i.e. stakeholder-, model-, and system-oriented goals. Our survey confirmed this impression indicating that all answers were in the upper range of the Likert scales. We also got valuable feedback for improvements that will influence the software's further developments.

Concerning stakeholder-oriented criteria, Participant 3 identified an applicability of *NESSI4D*$^{web+}$ as a teaching example in universities and state-planned construction projects. They estimated the potential for use cases high for Indonesia as the country's government has committed to the SDGs and has a large market for renewables. With Participant 1, we discussed the applicability of the building and neighborhood simulation. They regarded the building simulation as more suitable for cities where cooperation between neighbors might be difficult to achieve and citizens are more interested in concentrating on their houses. For rural villages, they perceive an application opportunity

Table 2 Input data for the representative village in Madagascar

Component	Input	Value	Based on
Central power grid (CPG)	Installation price	32000 USD	The World Bank (2019)
	Operation cost	0 USD/a	Assumption
	Electricity price	0.119 USD/kWh	Valev (2020)
	GHG emissions	0.538 $kg_{CO2\text{-}eq.}$/kWh	EIB (2020)
	Outage cycle and duration	0 h and 0 h	Assumption
Island grid	General expenditures at the project's beginning	6400 USD	Reber et al. (2018)
	General operation cost	128 USD/a	Reber et al. (2018)
Photovoltaic systems (PV)[a]	Capacity	1 kW	Assumption
	Tilt angle	18°	Jacobson and Jadhav (2018)
	Orientation	North	Jacobson and Jadhav (2018)
	Efficiency	20%	Assumption
	Specific purchase price	1200 USD/kW	IRENA (2020)
	Specific operation cost	9.5 USD/(kW*a)	IRENA (2020)
Locally produced wind turbine (WT)[a]	Number	1	Assumption
	Hub height	15 m	Kroeger (2022)
	Rotor radius	1 m	Kroeger (2022)
	Rated power	1 kW	Assumption
	Wind speeds (Cut-in/out, rated)	2.5 m/s, 16 m/s, 6.8 m/s	Assumption
	Specific purchase price	1500 USD/kW	Kroeger (2022)
	Specific operation costs	91 USD/(kW*a)	IRENA (2016)
Diesel generator (DG)[a]	Rated power	1 kW	Assumption
	Minimum load ratio	30%	Reber et al. (2018)
	Efficiency	26%	Aberilla et al. (2019)
	Specific purchase price	400 USD/kW	Reber et al. (2018)
	Specific operation cost	25 USD/kW + 0.023 USD/kWh	Reber et al. (2018)
	Diesel price	0.898 USD/l	Valev (2020)
	GHG emissions	0.267 $kg_{CO2\text{-}eq.}$/kWh	GOV.UK (2017)
Second-life battery storage (BS)[a]	Usable capacity	3 kWh	Assumption
	(Dis)Charging power	2 kW	Assumption
	Efficiency	91%	Kamath et al. (2020)
	Initial load ratio	0%	Assumption
	Specific purchase price	108.33 USD/kWh	Kamath et al. (2020)
	Specific operation cost	0 USD/(kWh*a)	Kamath et al. (2020)

[a] The lifetime for all components is assumed as the project length: 20 years. No feed-in tariffs are assumed

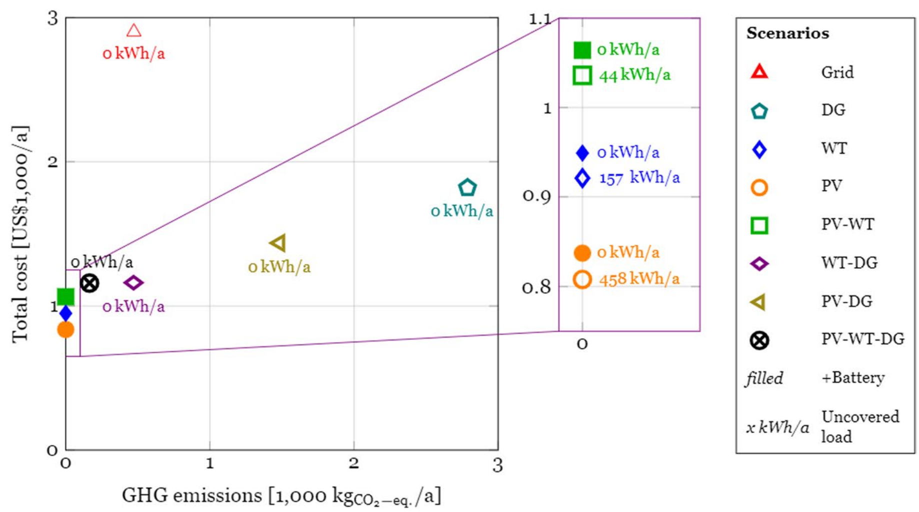

Fig. 4 Technical, economic, and ecological performance of the analyzed energy systems for an exemplary neighborhood in Madagascar

for the neighborhood simulation. Especially regarding Indonesia, they judged that the motivation to apply RETs and use a tool like *NESSI4D^{web+}* is low in cities because energy is too cheap and has good availability. In rural regions and islands, where reliability of the energy supply is lower or people are dependent on DGs, people might be more likely to use *NESSI4D^{web+}* to plan more reliable RESs. Regarding user characteristics, Participant 5 considered a basic educational degree essential to apply the artifact. They see detached housing owners, apartment managers, and middle-sized companies as potential addressees of the artifact. For other user groups, improvements regarding, e.g., language and currency options, would be necessary. As Participant 6 is concerned about the accessibility to the required input data, i.e. energy demand data, and comprehensibility of the software for inexperienced users, they see an application of *NESSI4D^{web+}* as an aiding tool for NGOs in communication and cooperation with locals rather than independent usage. Participant 3 raised the question of the perceived credibility of free web tools found on the internet regarding potential data phishing or other ulterior motives. The association with a foreign research institute might not be sufficient to build up trust in local companies. Instead, they suggested that charging a usage fee increases the perceived credibility. Alternatively, they suggested cooperating with a local university or actively approaching potential users to increase trust. Thereupon, we specifically asked Participant 6 and 7 about their experience and judgment regarding this topic. Participant 6 did not face particular difficulties during research in rural villages in Tanzania but also suggested local cooperation and highlighted the importance of information in the local language. Participant 7 suggested keeping governmental ties in the case of possible commercialization to maintain their current level of trust.

Concerning model-related criteria, we first asked if such DSS is deemed suitable for the ultimate goal of facilitating the energy planning process, which was uniformly affirmed. Participant 1 stated that the changing economic situation is not predictable with such a tool. Similarly, Participant 5 expressed that the complexity of certain systems was not fully reflected realistically. However, both highlighted that for the tool's functionality as first-decision support these aspects do not undermine the tool's efficacy and utility. In accordance, our survey depicted that all interviewees were confident in the software's reflection of reality. Participant 7 suggested disclosing the used formulas as an embedded PDF to further increase trust in the software's solutions. All participants agreed that the input and result variables were comprehensive and comprehensible. For further software development, Participant 7 suggested integrating an opportunity to generate load profiles from appliance usage data. Other valuable suggestions from the interviewees were the inclusion of building materials, refurbishments, and modernizations into the calculations, the return of investment (ROI) as a further key performance indicator, social factors, such as the maintenance of energy systems after implementation, the option to consider selling carbon certificates, and bidirectional electric vehicle charging. Participant 6 discussed the locals' possibly low familiarity with physical units and suggested alternative metrics, such as hours of equipment operation, i.e., how long a television can run on the electricity generated. On the other hand, Participant 7 reported that citizens of developing countries have high knowledge about energy consumption and saving due to familiar energy insecurities.

Concerning system-related criteria, we found high satisfaction with the software's design, speed, and available information, i.e. user manual and info texts. The interviewees also positively addressed the guidance through the web tool via individual web pages and progress bar. Participants had differing opinions on the sufficiency of the provided language and currency options. Participants 2 and 3 regarded English as sufficient for the potential stakeholders they identified. Participant 1 also regarded the currency USD as sufficient for Indonesian applications as the fluctuation of the local currency is higher. However, Participant 4 and 5 considered local languages and currencies as imperative for the successful dissemination of *NESSI4D*$^{web+}$ in India. This was strengthened by Participant 6 and 7 who also found local language options important for applications in rural areas. Regarding the complexity and accessibility challenges for particular user groups, most participants indicated that realistic templates are of high relevance to support users and more templates should be offered. As the prototype of *NESSI4D*$^{web+}$ is not able to provide templates for every country, Participant 1 suggested the provision of a generic template with average values to provide a starting point for every user. With regards to the accessibility of *NESSI4D*$^{web+}$, mixed responses were given. While Participant 1 is confident that stakeholders planning an energy system will have Internet access, Participant 6 raised concerns about such access in remote areas. Participant 1 further positively reacted to *NESSI4D*$^{web+}$ vast accessibility options, e.g., its usage via smartphones, and rates this factor as vital for projects in developing countries. Further, the option of sharing results with peers via a messenger app is described as highly valuable.

Discussion

Interpretation, implications, and generalized recommendations

Generally, we have found through software demonstration and evaluation that our web tool has the potential to empower decision-makers by facilitating the planning process of decentralized RESs, raising awareness of the economic, ecological, and social impacts of RETs, and supporting the formulation of data-based policies. We can, thus, presume that our research goal to support the SDGs bottom-up and top-down, increase energy independence, and ultimately impact society positively, has been well achieved.

Regarding our demonstration, we have shown the user's opportunity to reflect location- and situation-specific energy characteristics with our tool digitally. Through *NESSI4D*$^{web+}$*'s* ability to quantify and illustrate the economic and ecological impacts as well as the reliability of individual energy systems, the user is enabled to make informed decisions towards certain energy technologies, formulate policies, or, simply, educate. To increase the societal impact, such a tool and the ensuing decisions must be available to and made collaboratively with all stakeholders to allow the inclusion of individual goals and needs and careful formulation of data-driven strategies while simultaneously avoiding decisions based on secondary information from third parties. Due to the differing energy market, local characteristics, and uncertainties, we further emphasize the importance to conduct various in-depth simulations and analyses using *NESSI4D*$^{web+}$. Even though *NESSI4D*$^{web+}$ does not go beyond first-decision support, it empowers the people and strengthens the understanding of the RETs' impacts on various dimensions. As one of the interviewees said: it is crucial to democratize renewable energy, solely top-down decisions that are often rigid and time-consuming may not be sufficient to reach the SDGs in time.

Regarding our evaluation, we have earned positive feedback for the three evaluation criteria stakeholder, model, and system. Specifically, the latter dimension that encompasses the design, speed, and given information exceeded the expectation of the participants. However, two main controversial and interdependent key aspects transpired, i.e. user group and credibility. Regarding the users, the received feedback from interim discussions about citizens not being suitable addressees due to the tool's complexity was strengthened, although responses varied. A basic educational degree was found to be the minimum requirement for our tool. Businesses, educational institutions, NGOs, and policy makers were considered to be a more appropriate target group. Citizens would be able to use the tool mostly in cooperation and communication with such entities. However, as our goal states, we wish for decision support for all stakeholders across expertise and countries. We will, therefore, keep our stakeholder definition open at the moment to increase societal impact, but are well aware of the difficulties this entails. As we promote the software in different developing countries, we will adjust the potential targets according to the evaluation feedback, seeking out local cooperation. To improve the accessibility of digitization through tools like ours, we advise and intend to arrange free courses and a help desk to train and empower stakeholders. Even though one interviewee suggested that citizens of developing countries may already have high knowledge about energy consumption and saving due to familiar energy insecurities, we advise improving their literacy and technical skills towards both, RETs and DSS, through policies, regulations, and reforms. In light of the SDGs, these implications also address international organizations and developed countries. One disagreement among the interviewees was the language options. While some interviewees deemed English to be sufficient, others emphasized the need of incorporating local languages to increase accessibility. We, therefore, advise software developers and researchers seeking high user rates to explore the inclusion of local languages to ensure a large societal impact. The second disagreement between our interviewees regarded the software's credibility.

As emphasized above, we offer *NESSI* as a web tool to be usable for all, i.e. without costs, easy to use, and usable on various devices. However, we have found these exact characteristics to raise suspicions for some interviewees. Fostered by famous data protection scandals of other web tools, one reason might be the general aversion towards personal data insertions on websites due to concerns about the further usage of the data. Another reason might be the common mistrust towards free things which is deeply integrated into our cultures through sayings such as "nothing comes free in life". Several interviewees considered the authors' affiliation with a research institute provides sufficient credibility and trust. Other participants, however, doubted a foreign university to be sufficient to eliminate these concerns, specifically for stakeholders in developing countries. It was suggested to increase the credibility through local collaborations with academia and practice, intensified communication, and training. It is noteworthy that these suggestions implicate that dissemination and use of innovation are dependent on either existing networks or strong marketing efforts. The former raises the question if trust is only inherent to those who already have the network. The latter suggests that the authors' work should now shift from research to marketing. This raises the question of how many tools with significant societal impact may exist with developers and researchers that do not have such a network or resources for marketing. We, therefore, advise the community to implement free networks that are accessible for all, support and empower such research innovations, and disseminate the tool for maximum societal impact.

The often opposing statements of the interviewees have shown the complexity of energy system planning and strengthened the need for facilitation. Further extensive user testings and evaluations are necessary to collect in-depth feedback and gain insights on the knowledge levels, needs, and wishes regarding our tool of different user groups in various developing countries. Next to the practical contributions of our work, we see a value in $NESSI4D^{web+}$ as a research tool to conduct more and in-depth case studies worldwide. We demonstrated some potential analyses in this and previous works and showed further areas of applications. In summary, we complied with our research question and built a system that is able to assist stakeholders in developing countries to sustainably build and transform local energy systems.

Limitations and further research

We distinguish between demonstration-related, approach-related, and DSS-related limitations. Regarding the former, our generated load profiles depend strongly on the quality and actuality of the used data. We consider load profiles synthesized from detailed household surveys a sufficient approximation for planning an energy system. Since users can upload their own data, these circumstances do not limit the functionality of our software. Regarding the environmental results, we only considered operative GHG emissions and omitted life cycle impacts. Thus, these results are positively skewed towards RES for all components. Further, we assessed social and institutional aspects that significantly impact the sustainability of an energy system only qualitatively. Consequences of governmental frameworks, energy or management policies, and predicted developments were not part of the demonstration. Regarding our approach, the evaluation is missing the first-hand perspective of non-expert citizens as we primarily focused on expert interviews. Another limitation is the fact that we did not narrow our stakeholder group.

Further research could include identifying a specific stakeholder group and developing the software specifically for that audience, or creating different versions of the software, each targeted to a specific user group. DSS-related shortcomings include the performance dependency on user devices and literacy, electricity availability, and a reliable Internet connection of a web solution in general. Further, simplifications are necessary for simulation approaches including their inability to reflect on political, economic, and environmental uncertainties. Thus far, we have not incorporated the cultural dimension, maintenance, and construction. We omitted line losses and used hourly time steps. Since $NESSI4D^{web+}$ is a prototype, more language options, pre-generated load profiles, components, and financial parameters will be implemented as suggested by the evaluation participants. Due to the different challenges and needs of the users, we follow Walling and Vaneeckhaute (2020) and expect several suitable energy system combinations whose selection is based on the subjective preference of the decision-maker. Therefore, we avoid explicit recommendations by the software. Further developments of the software may incorporate RAMP's features to facilitate the synthesis of load profiles. Scoring models to quantify the social impacts of energy systems can also be incorporated.

Conclusions

Energy system planning and transition is a demanding task, as stakeholders are challenged by the complex characteristics of energy components, on-site conditions, and consumer-specific energy requirements. Barriers can be especially high in developing countries. Motivated by the calls in the IS community for solution-oriented research, we developed a comprehensive DSS to promote economic, ecological, and social sustainability through decentralized energy systems with the ultimate goals of supporting the SDGs, empowering locals, and enabling the very prerequisite of digitization: reliable electrification. To enable accessibility to all stakeholders, we implemented an open-access web tool tailored to the goals and needs of stakeholders in developing countries. We demonstrated how $NESSI4D^{web+}$ supports users in their decision-making process for viable energy systems and evaluated it through interviews with stakeholders and experts. We got positive feedback regarding the three evaluation criteria stakeholder, model, and system, and various ideas for further development. Controversial aspects remained the appropriate user group and the credibility of open access web tools. $NESSI4D^{web+}$ contributes to practice as a measure to meet the SDGs and to theory as a research tool.

Abbreviations

BS	Battery storage
CPG	Central power grid
DSS	Decision support system
DSR	Design science research
DG	Diesel generator
GHG	Greenhouse gas
ICT	Information and communication technology
IS	Information systems
NESSI	Nano Energy System Simulator
NESSI4D	Nano Energy System Simulator for Development
NGO	Non-governmental organization
PV	Photovoltaic system
RES	Renewable energy system
RET	Renewable energy technology
SDG	Sustainable development goal

USD	US Dollar
WT	Wind turbine

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Declarations

Ethics approval and consent to participate
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Consent for publication
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