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Tool-based renewable energy system planning using survey data: A case study in rural Vietnam

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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 artifact's 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 method's 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

List of symbols

Units

a	Year
%	Percentage
W	Watt

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kW	Kilowatt
kWh	Kilowatt hours
kg_{CO_2}-eq.	Kilogram carbon dioxid equivalents
US$	United States dollar
VND	Vietnam dong

Simulation models

HOMER	Hybrid optimization of multiple energy resources
iHoga	Improved hybrid optimization by genetic algorithms
NESSI	Nano energy system simulator
NESSI4D	Nano energy system simulator for development
OnSSET	Open source spatial electrification tool
RAMP	Remote-areas multi-energy systems load profiles
Sure-DSS	Sustainable rural energy decision support system

Renewable energy technologies

BS	Battery storage
PV	Photovoltaic system
WT	Wind turbine

Renewable energy system scenarios

Grid	Central power grid
Grid–PV	Central power grid and photovoltaic system
Grid–WT	Central power grid and wind turbine
Grid–PV–BS	Central power grid, photovoltaic system, and battery storage
Grid–WT–BS	Central power grid, wind turbine, and battery storage
Grid–WT–PV	Central power grid, wind turbine, and photovoltaic system
Grid–WT–PV–BS	Central power grid, wind turbine, photovoltaic system, and battery storage

Abbreviations

DSR	Design science research
DSS	Decision support system
FIT	Feed-in tariff
GHG	Greenhouse gases in kg_{CO_2}-eq.
ICT	Information and communication technologies
ICT4D	Information and Communication Technologies for Development
IS	Information systems
O &M	Operation and management
SDG	Sustainable development goals
TVSEP	Thailand Vietnam Socio Economic Panel
RET	Renewable energy technologies
RES	Renewable energy systems
UN	United Nations

1 Introduction

Access to electrical and thermal power allows to fulfill basic human needs and has proven to alleviate economic growth, transform societies, and raise living standards (UNDP, 2016; Oliveira & Moutinho, 2021). The trend toward an electricity-based economy has increased the importance of electric supply to provide equal economic chances (UNDP, 2016). Although the energy situation has improved worldwide in the past decades, 13 % of the population still lacks access to a reliable supply (United Nations, 2021). Dependence on fossil fuels, which provide 70 % of global demand, leaves players vulnerable to supply shocks, price changes, and political friction (Al-falahi et al., 2017; UNDP, 2016). Moreover, fossil fuels generate greenhouse gas (GHG) emissions that reinforce global warming and have adverse impacts on people's well-being (United Nations, 2020). Therefore, the United Nations have formulated the 17 Sustainable Development Goals (SDGs) which include the global objective for access to affordable, modern, reliable, and sustainable energy for all (United Nations, 2021). Great potential lies particularly in the building sector, where a share of 22 % of global end-use energy is consumed and 17 % process-related GHG are emitted (IEA, 2019). Renewable energy technologies (RETs) contribute significantly towards more sustainable energy use in developing countries, as they are able to supply remote areas with modern electricity in an economically and ecologically viable manner, or to relieve the often overloaded electricity grids (Nong et al., 2020; Mandelli et al., 2016a). Additionally, new technologies such as heat pumps and co-generation plants have emerged, allowing to design energy supply holistically as multi-energy systems. Cooperative generation in microgrids and heating networks offers great opportunities for cost and emission reductions. However, to promote the usage of RETs, stakeholders need to be informed about their technological capabilities as well as economic, ecological, and social impacts. Especially in developing countries, stakeholders face the challenge of complex energy components' technical specifications, geographic and weather conditions, and consumer-specific energy demands in order to implement suitable energy systems (Al-falahi et al., 2017; Erdinc & Uzunoglu, 2012). Scarce data and the lack of studies in developing countries further complicate the formulation of evidence-based strategies and policies (Oliveira & Moutinho, 2021). Programs have been incorporated globally, but these often fail to include the users' needs and views. Social and cultural issues of target communities result in low acceptance leading to long-term failures (Urmee & Md, 2016). Therefore, this work argues that stakeholders at the site must be assisted directly in their decision process for an economical, social, and ecologic sustainable energy composition. Mathematical models and Information and communication technologies (ICTs) provide new opportunities to reduce complexities, especially in developing and transitioning countries (Walsham, 2017). Thus, energy system planning and energy policy formulation are often supported with decision support systems (DSSs) (Cherni & Kalas, 2010). However, these tools are often commercial, need programming knowledge or are not suited for rural contexts in developing countries, see Sect. 2. Thus, following several calls for inter-disciplinary development and solution-oriented research (Lehnhoff et al., 2021; Gholami et al., 2016; Siksnelyte et al., 2018), this work addresses the following research question:

> *How can stakeholders in developing countries make informed decisions to sustainably build and transform decentralized energy systems?*

A Design Science Research (DSR) process according to Peffers et al. (2007) is conducted to develop a tool-based process to analyze small energy systems with scarce data and little capacities. The process includes the generation of input data that fulfills the conditions of detail, location-specificity, and topicality. This covers the synthesis of load profiles from survey data with the software RAMP and the inclusion of location-specific parameters. Second, the energy simulation software NESSI by Kraschewski et al. (2020) is modified and extended for the needs of stakeholders in developing countries and included in the process model. The research design is described in Sect. 3 and the resulting artifact is presented in Sect. 4. In Sect. 5, the method is tested and applied to a sample of thirty rural households in the Thua Thien-Hue province in Vietnam where the lack of information, data, local expertise, and scientific research was identified as a major challenge for the wide-spread use of RETs (Nguyen & Tuan, 2015; Nong et al., 2020). In Sect. 6, the results and their implications are evaluated, before limitations and deducing future research are highlighted in Sect. 7 and a conclusion is given in Sect. 8.

2 Literature review

2.1 Information systems for sustainable development

The United Nations (UN) defines sustainable development as a way to meet present needs without compromising the ability of future generations to satisfy their own needs (United Nations, 2021). This requires the enhancement and balance of inter-correlated economic, ecological, technological, and social conditions through individual, national, and international efforts (Siksnelyte et al., 2018). The UN has therefore agreed on 17 interrelated, but also sometimes mutually exclusive SDGs that define the common efforts to achieve a sustainable future (United Nations, 2021). As economies increasingly rely on electricity, the energy sector plays a significant role in sustainable development as it (among others) enhances living standards, increases international and national competitiveness, and transforms societies (UNDP, 2016; Oliveira & Moutinho, 2021). Simultaneously, the impacts of climate change that are further exacerbated by fossil fuel consumption call for a rapid energy transition, see SDG 7 (United Nations, 2021). However, inter-disciplinary decision-making is required to achieve the often contradicting goals of economic viability, energy resilience, and environmental friendliness (Siksnelyte et al., 2018). Broad consensus is found on the positive impact of decentralized hybrid energy systems such as mini- and micro-grids that mainly run on RETs (Balderrama et al., 2020; Herraiz-Cañete et al., 2022). However, the widespread dissemination of RETs is often hindered by missing knowledge about their long-term positive impacts or low transparency on the decision making process of third parties. Further, designing such systems is often overwhelming and requires detailed information on the energy components' technical specifications and inter-correlations, local geographic and weather conditions, consumer-specific energy demands, market data, and soft social factors (Al-falahi et al., 2017; Erdinc & Uzunoglu, 2012). Deviations may lead to the inadequate choice and sizing of components, leading to high monetary burdens, low energy reliability, and sometimes long-term failure of the projects (Herraiz-Cañete et al., 2022; Urmee & Md, 2016). Thus, specialized DSS are necessary to reduce those complexities. The IS community acknowledges this need and implies that "Energy + Information > Energy," i.e., information is needed to enable and support economic and behaviorally driven solutions when designing energy systems

(Watson et al., 2010). Walsham (2017) identified environment and climate change as the major societal issues of our century that must be addressed in the realm of Information and Communication Technology for Development (ICT4D). Thus, research that works on integrating and cooperating set of people, processes, software, and information technologies to support individual, organizational, or societal goals are called for (Watson et al., 2010; Gholami et al., 2016). Lehnhoff et al. (2021) further elaborates that IS research does not have to be theory-building at once, but must provide solutions for practical applications. Especially in the field of energy supply, access, and distribution, ICTs can effectively support stakeholders in developing and transitioning countries. However, despite its relevance, only few research provides national or empirical insights for policymakers or explicitly refer to the SDGs (Leong et al., 2020).

2.2 Related energy system simulation tools

Mathematical models, specifically multi-criteria decision support systems, have proven to address the challenges of energy system planning adequately. They allow to compare alternatives, rank target values depending on individual goals, and find suitable designs. In the past decade, a series of computational models have been developed for energy planning and found widespread research and practical applications, see Mandelli et al. (2016a) and Mahmud et al. (2018). Widely-known tools are HOMER Pro (link) or iHoga (link) which conduct comprehensive techno-economic optimizations determining optimal sizing of components and minimizing net cost (HOMER Energy LLC, 2022; Dufo López, 2022). They have successfully been employed for case studies covering developing countries, see, e.g. Vendoti et al. (2021), Lau and Tan (2021), and Gebrehiwot et al. (2019). However, these tools often focus on the electric infrastructure, with only secondarily treating thermal loads. They further mostly require expert knowledge, often apply optimization algorithms which need high amounts of computing power, and were not explicitly designed for developing countries. In addition, their often commercial nature prevents stakeholders from using them. SURE-DSS by Cherni and Kalas (2010) uses a people-centered sustainable livelihood approach to plan the electrification of remote regions, but it is not an energy system simulator. OnSSET (link), another established tool employed in developing countries, see Balderrama et al. (2020), requires programming knowledge and focuses solely on electrification. However, hot water and heat demands cannot be ruled out systematically to allow for analyses of countries or provinces in colder habitats. Stevanato et al. (2020) employ MicroGridsPy (link), an open-source modeling framework for the optimization of hybrid micro-grids. However, it also does not have a graphical user interface, thus, limiting its widespread application. Another known energy system simulator is EnergyPLAN (link), which has been used for case studies in both developed and developing countries, e.g. Ecuador, Tanzania, and Nicaragua (Lund et al., 2021). Although the freeware includes a variety of functionalities, it has been developed primarily for national-scale energy systems (Lund et al., 2021). The multi-energy tool NESSI by Kraschewski et al. (2020) is specialized in decentralized energy systems. The software focuses on its usability with a rich graphical user interface for stakeholders like building owners and politicians. However, NESSI was designed for applications in developed countries and potentially subject to built-in biases (al Irsyad et al., 2017).

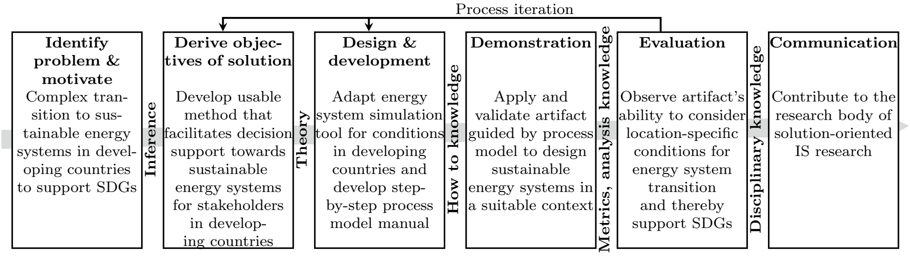


Fig. 1 Design science research methodology adapted from Peffers et al. (2007)

2.3 Load profile generation for energy system simulation tools

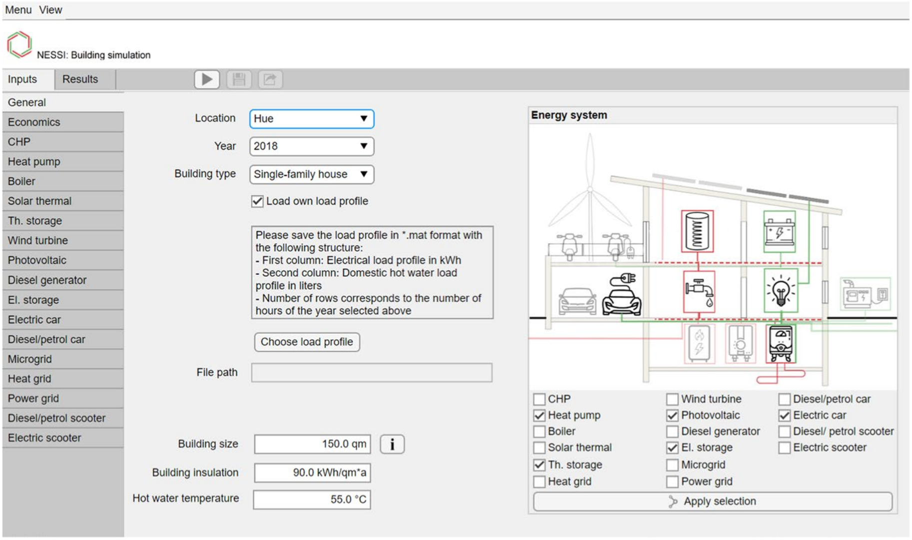
Energy system analysis tools depend on suitable load profiles. Obtaining such load profiles is challenging and in developing countries often missing as they require information on household characteristics, a sufficient level of detail, and must be topical. Most simulation tools offer a library of pre-defined load profiles that are often not fitting for individual cases due to different cultural, social, and economic conditions (Proedrou, 2021). The tools HOMER Pro, iHoga and NESSI allow to import hourly or average user load data (Dufo López, 2022; Kraschewski et al., 2020). However, this data is often missing in developing countries. HOMER Pro additionally allows to import U.S.-American facility profiles from the OpenEI database and apply a similarity measure based on the Koeppen Geiger Climate Classification Index (HOMER Energy LLC, 2022). This is not sufficient in the context of rural areas in developing economies as the people's living conditions differ considerably from those in industrial countries. Thus, in the reviewed body of literature, several tools, models, and methods are discussed to synthesize load profiles, see e.g. Marszal-Pomianowska et al. (2016) and McKenna and Thomson (2016). However, most tools are fed using data from detailed activity diaries, national time-use surveys, or device ownership statistics, and are context-specific to particular cases in developed countries or urban areas. For the developing world, an approach is needed that is able to cope with the dynamic settings at the site and inexact data. The software RAMP (link) by Lombardi et al. (2019) was specifically designed to generate high-resolution load profiles in developing countries. RAMP simulates users' appliance habits accounting for the device's nominal capacity, frequency of use, and total daily functioning time. Randomly varying parameters allow considering uncertainty and irregular usage behavior (Lombardi et al., 2019). The software is considered among the richest and most functional tools with respect to flexibility and customizability (Herraiz-Cañete et al., 2022).

3 Research design and methodology

No tools were found that meet the requirements of providing targeted decision support for sustainable multi-energy systems in developing countries (see Sect. 2.2). Thus, following the calls in the IS community for more solution-oriented research (Lehnhoff et al., 2021), an intuitive method for the design, transformation, and evaluation of energy systems in developing countries when data is scarce is developed using the design-science-oriented approach by Peffers et al. (2007) shown in Fig. 1. In the IS community, DSR is a popular problem-solving paradigm that aims to improve technical and scientific knowledge through the development of innovative artifacts. Its potential to contribute to society's critically needed sustainability transformation is explicitly highlighted (vom Brocke et al., 2020). Research outcomes of DSR can be design artifacts or design theories (Baskerville et al., 2018). Gregor and Hevner (2013) define three levels of DSR research contribution types: situated implementation of artifact, nascent design theory, and well-developed design theory about embedded phenomena. Multiple research processes exist in DSR, most prominently by Hevner (2007) and by Peffers et al. (2007). This work uses the process by Peffers et al. (2007) consisting of the 6 steps (1) identify problem and motivate, (2) derive objectives of solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. The process is iterative, feeding back lessons learned into earlier steps. For the problem identification of this work, see Sects. 1 and 2. As a basis for the artifact, NESSI by Kraschewski et al. (2020) is used. In the design and development stage, NESSI is adapted and expanded to account for circumstances in developing countries. The new tool is called NESSI4D. Further, the usage of NESSI4D is described in a process model that serves as a comprehensive decision support manual for stakeholders that aim to design long-term sustainable energy systems. The process model also includes the usage of RAMP, a load profile generation tool that was identified in the literature review (Sect. 2.3). The development and resulting artifact are described in Sect. 4. In the fourth stage, the applicability is demonstrated and validated in a carefully constructed case study as is common in DSR (Peffers et al., 2012) and DSS literature (Arnott & Pervan, 2012), see Sect. 5. In Sect. 6, the tool is evaluated and discussed. The artifact contributes not only practically but also theoretically by providing a research tool for conducting in-depth case studies in developing countries.

4 Artifact description

The Nano Energy System SImulator NESSI by Kraschewski et al. (2020) is specialized in decentralized energy systems. It simulates thermal and electrical energy flows, total costs, and GHG emissions. The simulation procedure is visualized in Fig. 4 step (ii). It is built upon DSR following software engineering guidelines. In this work, NESSI is adapted and expanded to account for circumstances in developing countries. For this purpose, the electric infrastructure is extended by small-scale wind turbines (WT) and diesel generators, to adapt to existing energy market structures and raise the flexibility as well as the robustness of the system. Given the developments in electric mobility and the cost advantages of electric two-wheelers, the simulation of battery and fuel-powered light motorcycles is also enabled. Models regarding the national power grid were altered to represent its availability in developing countries. Thus, the user is now able to simulate power system expansions and potential outages. For the case of an absent power grid and no storage possibilities, a reactive load is incorporated to use excess energy to heat a body of water. The economic calculations were improved by adding the U.S. dollar (USD) as a further currency option. Particularly in developing countries, microgrids provide an opportunity for electrification in remote areas where grid expansion is economically or technically infeasible. Additionally, they support the integration of distributed energy sources and reduce losses through shorter transmission distances (Nong et al., 2020; Mandelli et al., 2016b). Thus, to allow for off-grid applications an island power grid is included. Additionally, the option of combining



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

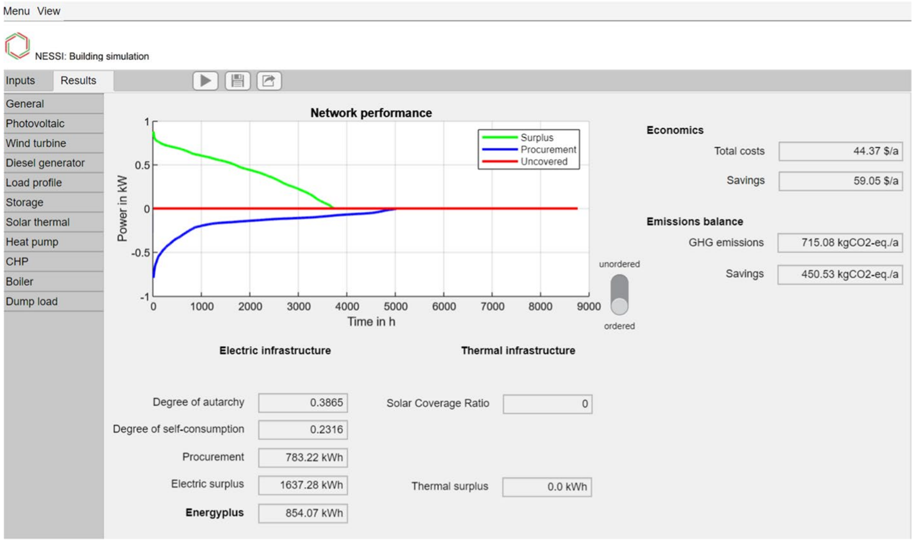
Hot water temperature: 55.0 °C

☐ 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

Fig. 2 NESSI4D's graphical user interface

building analysis results to examine neighborhoods and villages is implemented. A high level of detail and flexibility is maintained by combining the results after simulating carefully constructed individual houses. The rich graphical user interface, optional country-specific standard input data for the components, underlying weather data, numerous currency options, and an extensive country-, building-, and household-specific load profile library, support users in performing simulations. To overcome the challenge of missing energy demand data, the user can choose load profiles from the library that were generated from detailed household survey data which were previously synthesized using RAMP by Lombardi et al. (2019). Alternatively, load profiles owned by the user can be imported. In summary, the model of the software has been extended with respect to the unique circumstances of the energy system in developing countries by including new energy producing, consuming, and storing components, changing underlying assumptions, and allowing for neighborhood simulation. For a visual impression of NESSI for Development (NESSI4D), see Figs. 2 and 3 or the Online Resources.

To further assist stakeholders that aim to design long-term sustainable energy systems, a comprehensive decision support manual was developed, depicted in Fig. 4. The detailed step-by-step approach considers indicators that greatly influence the system's final architecture and technical, economic, and ecological outcomes. First, the country's situation, stakeholders' objectives, and international literature must be assessed to evaluate the available technologies and possible barriers. Input data must be compiled or synthesized which includes detailed information on energy demand, geographic conditions and climate, as well as available technologies at the site, their settings, and local prices. It is emphasized that the inclusion and diligent consideration of each parameter is indispensable in the decision-making process to ensure the longevity of the energy project. To meet this need, this tool is designed to guide the user through each step and parameter of the process. Secondly, fitting energy system scenarios have to be formulated carefully and simulated with the software NESSI4D.



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

Fig. 3 NESSI4D's graphical user interface: results

Sensitivity analyses are advised that go beyond the chosen scenarios to test the robustness of the simulation's outcomes. Finally, the results must be interpreted thoroughly, taking into account country- and context-specific factors.

5 Demonstration: rural community in Thua Thien-Hue, Vietnam

5.1 Step 1: assess the country's situation, stakeholders' goals and international literature

In the last years, improvements in the energy sector enabled quality increases of electricity supply, reduction of outages as well as grid expansions to virtually every household in Vietnam (Hien, 2019). Currently, stakeholders are faced with a rapid increase in energy demand due to rising prosperity and population growth. Ongoing investments to expand the grid's capacity and agility, as well as the energy-generating infrastructure, are indispensable to ensure the continued reliability of the power supply (Nong et al., 2020). In rural areas specifically, the extension or reconstruction of the grid is often timely and economically impracticable, because of complex geographical conditions, low population density, and the households' little energy demands (Gebrehiwot et al., 2019). Frequent occurring grid overloads further strengthen the need for alternative solutions, such as decentralized systems based on renewable energies (Nong et al., 2020).

Until now, electricity was mainly sourced from hydropower, natural gas, and coal (Dapice, 2018). As these resources are considered exploited and finite, the rising electricity load is met with imports and a stronger focus on coal mining. The Vietnamese government has set its energy targets oriented toward RET, specifically hydro, wind, and solar energy by committing to reduce GHG emissions by 25 % until 2030 at the 21st Conference of the United Nations Framework Convention on Climate Change (Dapice, 2018).

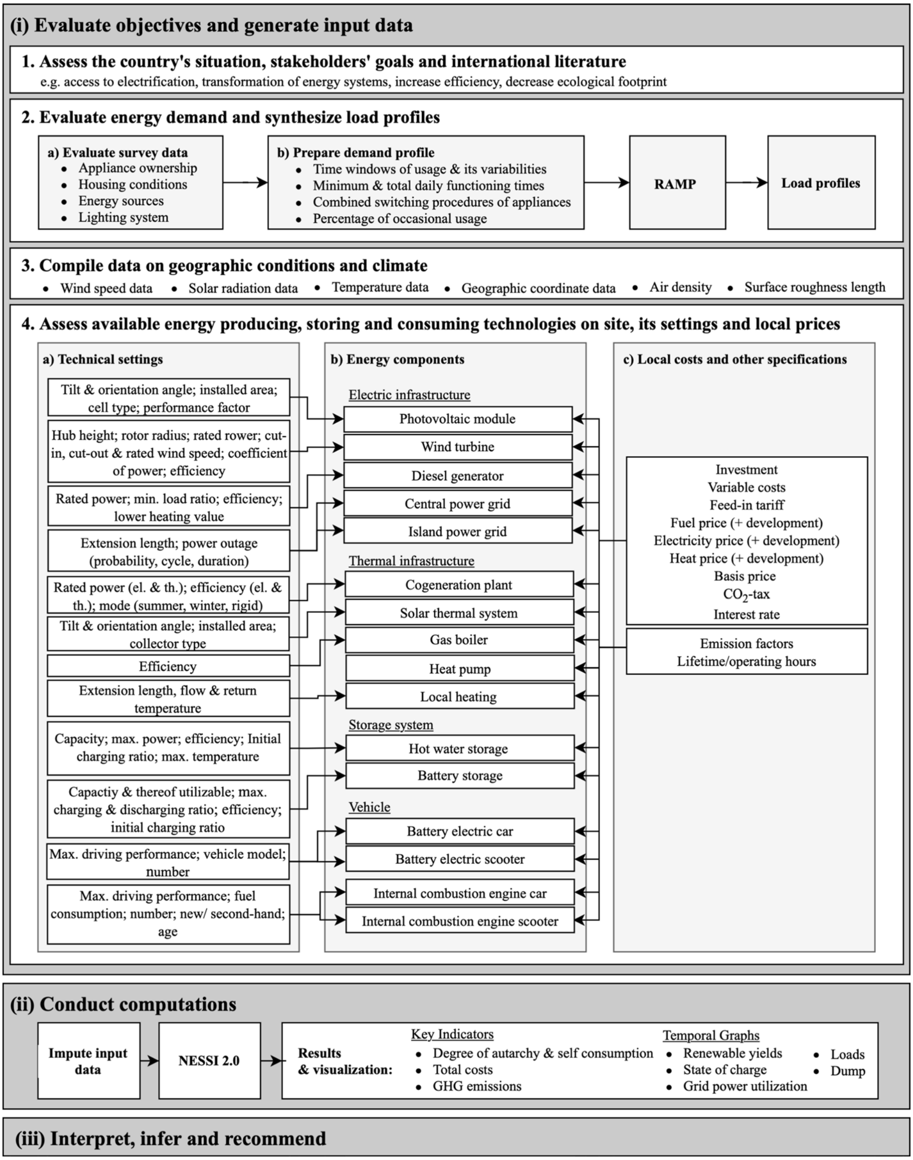


Fig. 4 Process model

Peer-reviewed studies for Vietnam of the past 10 years have been mainly regarding the country's overall energy situation, e.g., Nguyen and Tuan (2015); Min and Gaba (2014), Zimmer et al. (2015), and Huong et al. (2021), consumption behavior, e.g., Hien (2019), renewable resource potentials and implementation challenges, e.g., Phap et al. (2020), Polo et al. (2015), Tran et al. (2016), and Nguyen et al. (2014), as well as energy or environmental (protection) policies, e.g., Lan et al. (2019), Nong (2018), Nong et al. (2019), Coxhead et al. (2013). Several studies have evaluated the economics of renewable energy generating components and the relation between energy consumption, income, economic growth, foreign direct investments or emissions, e.g., Tang and Tan (2015), Phuong and Tuyen (2018), Morelli and Mele (2020), Phong et al. (2018), Phrakhruopatnontakitti et al. (2020), Tang et al. (2016), Son and Yoon (2020), and Long et al. (2018). Other articles regard the conventional strategy of expanding the national grid, e.g., Le et al. (2013). Several works have simulated the option of feeding the central power grid with large solar or wind renewable energy plants (Le et al., 2018; Truong et al., 2021; Viet et al., 2018). Nguyen and Van (2021) and Thanh et al. (2021) analyze a grid-connected rooftop solar system for a household in urban settings. Decentralized solutions in the rural energy conditions have scarcely been evaluated. Nguyen et al. (2019a) and Tran et al. (2021) analyze micro-grid design on Vietnamese islands with HOMER, but emphasize that further studies must be conducted where electricity is readily available. Nguyen (2007b) has examined this possibility through evaluating the economics of hybrid wind and solar stand-alone renewable energy systems (RES) for rural households. However, they applied inexact input data by assuming a constant energy demand and using rough weather data. They further do not include the option of implementing RETs supplementary to the power grid and the environmental impacts of the energy systems. Due to this lack of research, Nong et al. (2020) demand more scientific studies that do not only aid policy-makers in their strategy formulation, but also facilitate stakeholders to generate regional-specific inquiries.

5.2 Step 2: evaluate energy demand and synthesize load profiles

There have been several studies closing the gap of missing load data by forecasting the Vietnamese energy demand (Võ et al., 2020; Nguyen et al., 2019b, 2018; Lee et al., 2020). These studies focus on the industry and construction sectors or the overall electricity consumption. Inferences about rural demands are infeasible. Load profiles with data from the Thailand Vietnam Socio Economic Panel (TVSEP) of the year 2017, see tvsep.de, is generated. The survey contains information on 609 rural households in the low per-capita-income province Thua Thien-Hue in Vietnam. The households are selected based on a three-stage cluster sampling design and acknowledged to be representative for the rural population in this region (Hardeweg et al., 2013).

Most households comprise of couples with up to two children. Using an exchange rate of 0.000043 US$/VND, the annual mean income is 4,653 US$ per household and 1,265 US$ per capita. The houses have a mean size of 84.5 m^2 and three rooms on average. The majority uses electricity for lighting and bottled gas for cooking. Almost every household owns one television, refrigerator, and rice cooker, as well as three fans. Smartphones are less common with a share of 53 %. Other electrical appliances are owned infrequently in the sample as depicted in Fig. 5. Air conditioners, for example, are rarely owned, which might be due to the high costs of its operation (Le & Pitts, 2019).

As no information about the lighting system is available, the satisfaction of basic visual demand is assumed, concluding in the presence of one indoor light per room and one outdoor light per house. The assumptions of the assets' usage are dependent on the average time between sunrise and sunset, assumed working hours, and free-time behaviors. Selected appliances are considered to be used occasionally. Further information about the typical usage characteristics, and power needs per appliance, is obtained from Le and Pitts (2019); Mandelli et al. (2016b), and Lombardi et al. (2019). For simplicity, weekends, vacation

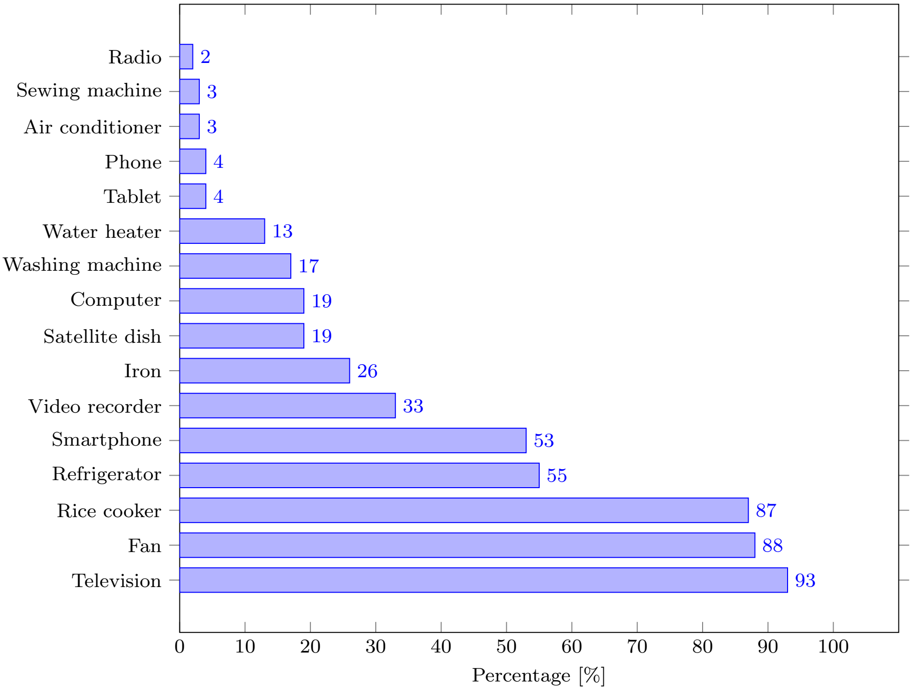


Fig. 5 Share of electrical appliance ownership in rural Thua Thien-Hue, Vietnam

Table 1 Assumptions of appliance usage based on the TVSEP, Mandelli et al. (2016b), Lombardi et al. (2019), and Le and Pitts (2019)

Appliance	P W	Cycle min	Total use min	Window 1	Window 2	Window 3
Indoor bulb	7	10	300	00:00–05:30	–	18:30–24:00
Outdoor bulb	13	10	180	00:00–05:30	–	18:30–24:00
Stand fan	55	5	525	00:00–07:30	12:00–13:00	18:30–24:00
Rice cooker	600	20	111	05:30–07:30	12:00–13:00	18:30–20:00
Television[a]	50	10	348	05:30–07:30	12:00–13:00	18:30–24:00
Refrigerator	150	30	1,440	00:00–24:00	–	–
Smartphone charger	5	30	180	00:00–07:30	12:00–13:00	18:30–24:00
Video recorder	30	5	34	05:30–07:30	12:00–13:00	18:30–24:00
Iron	1,200	5	20[b]	05:30–07:30	12:00–13:00	18:30–24:00
Computer	200	5	132	05:30–07:30	12:00–13:00	18:30–24:00
Washing machine	500	45	45[b]	00:00–24:00	–	–
Water heater	3,500	5	42	05:30–07:30	12:00–13:00	18:30–24:00
Tablet	50	5	205	05:30–07:30	12:00–13:00	18:30–24:00

[a] With satellite dish of 75 W

[b] Used occasionally

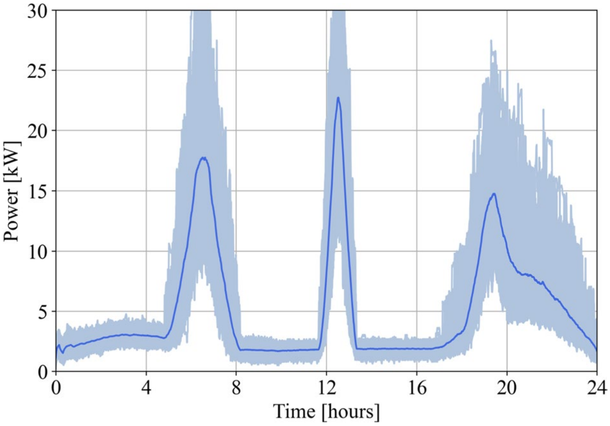


Fig. 6 Example of 365 different stochastic daily load profiles of the thirty rural households in Thua Thien-Hue

days, as well as the differentiation between seasons, are omitted. Table 1 summarizes the appliance's settings and its assumed usage.

For this analysis, thirty households are randomly chosen to form a representative, small village. The above-mentioned information is then used to generate load profiles with RAMP based on the households' individual asset ownership. In Fig. 6, the summation of these load profiles for one day is depicted. Interested readers find the characteristics and appliance ownership for each selected household in Appendix A in the Online Resources.

5.3 Step 3: compile data on geographic conditions and climate

Another critical factor for energy systems is the climate conditions at the site. Climate data is needed to enable the calculation of the components' energy yield. For instance, to obtain the PV module's yield, information on the diffuse, beam, and reflected solar radiation is needed. The WT's simulation requires wind speed data and air density. Depending on the country, different datasets are available with varying time steps. As this approach strives for a high degree of detail, data with minutely or hourly time steps is desired. This enables the analysts to interpret the results in more detail and discover weaknesses and limitations. Thus, location-specific data from the NASA-Merra2 dataset for wind and temperature data and Copernicus Atmosphere Monitoring Service for radiation data were compiled (CAMS, 2021; Renewables Ninja, 2021).

5.4 Step 4: assess available energy producing, storing and consuming technologies on site, its settings and local prices

Vietnam's wind and solar resources provide suitable conditions for related renewable energy generating components (Nguyen, 2007a; Tran & Chen, 2013; Phap et al., 2020; Polo et al., 2015). Thus, electrification via the grid is compared with systems that include supplementary photovoltaic modules (PV) and small scale WTs. Battery storage units (BS) are included due to their capabilities to smooth the RET's fluctuating yields and increase the system's efficiency (Gebrehiwot et al., 2019). The diesel generator is excluded since it does not fulfill the policymakers' desire to shift toward ecological sustainable energy systems. The evaluation of thermal energy is omitted, because the climatic conditions induce no heat demands. The warm water demand for showering or cooking is assumed to be fulfilled with the electric heater since no related data is available. Six RES with different combinations of thirty $6\,\mathrm{m}^2$ rooftop PVs, two WTs, and one BS for a representative grid-connected rural neighborhood are simulated and compared to the scenario of sole grid supply. The predetermined energy component settings, operation and management costs (O &M), and investments are summarized in Table 2. Because there are comparatively low wind speeds in the Thua Thien-Hue region, input data from a WT model designed for low wind speeds is used (Nord, 2020; Nguyen, 2007a).Costs of converters and inverters are assumed to be included in the components' prices.

Additionally, three sensitivity analyses to show the importance of simulations for the decision process are conducted. The first analysis accounts for future cost developments. Data suggests that RETs are becoming financially more attractive, whereas the electricity price in Vietnam is expected to rise continuously due to non-sustainable governmental subsidies (Le, 2019; Hiep & Hoffmann, 2020). The predicted electricity price development of 8.5 %/a, decreasing RET investments of 30 % by 2030, and further 20 % until 2050 (Dapice, 2018) is simulated. Second, the influence of policymakers through feed-in tariffs (FITs) is assessed. Especially in developing countries, FITs need to be set at an appropriate level to solve the implementation bias toward the rich and achieve access to modern electricity for the poor (Kobayakawa & Kandpal, 2014). Third, the potentials to reduce the value of initial investments is examined. Batteries, originally designed for electric vehicles, are expected to enter the energy market as reconditioned second-life batteries. For the residential sector, the batteries' capacity is sufficient and shows a high application potential as a cheaper alternative (Kamath et al., 2020). Additionally, WTs from the company Rivogy whose parts can be mostly manufactured at the site using local products (Kroeger, 2020) are included. Because of a lower-rated power per WT, a higher number of installed WTs to ensure the scenarios' comparability is assumed. Step-by-step screenshots of the analyses for one exemplary RES are provided in Appendices B and C in the Online Resources.

5.5 Step 5: conduct computations

First the results and findings of the base analysis is presented, comparing the simulated RES with a reference scenario which does not consider additional components. As no space heating is required, due to sufficiently high temperatures, the village's load comprises solely of electrical demand that sums up to 45,355 kWh/a. The components' prices result in investments of 37,944 US$ for the PVs, 44,500 US$ for the two WTs, and an additional 9,614 US$ for systems including BS. With the local conditions and selected RES settings, the WTs and PVs generate 36,683 kWh/a and 63,922 kWh/a, respectively. The degree of autarchy spans from 32 % (Grid–PV) to 66 % (Grid–WT–PV), whose values increase up to 90 % (Grid–WT–PV–BS) when a BS is added. Additional BS also have the potential to increase the degree of self-consumption, for example, from 60 % to 75 % in the case of Grid–WT.

Figure 7 summarizes the annual grid supply, GHG emissions, and total costs of each energy system. The latter is presented by a fixed annualized value and comprises

Table 2 Input data and technical settings for the village

Component	Input	Value	Based on
Project data	Project duration and lifetimes	20 a	Assumption
	Discount rate	5 %	Assumption
Central power grid	Electricity price[a]	0.081 US$/kWh	Valev (2020)
	Emission factor	0.913 kg_{CO_2}/kWh[b]	IGES (2020)
Photovoltaic systems	Rated power	30*1.2 kW_{peak}	Assumption
	Orientation	South	Jacobson and Jadhav (2018)
	Tilt angle	16 °	Jacobson and Jadhav (2018)
	Investment	1,054 US$/$kW_{peak}$	IRENA (2020)
	O &M costs	9.5 US$/$kW_{peak}$*a	IRENA (2020)
	Feed-in tariff	0.0806 US$/kWh	Prime Minister (2020)
Imported wind turbines	Rated power	2*8.9 kW	Nord (2020)
	Hub height	24 m	Nord (2020)
	Rotor radius	3.5 m	Nord (2020)
	Cut-in wind speed	2.5 m/s	Nord (2020)
	Rated wind speed	6.8 m/s	Nord (2020)
	Cut-out wind speed	16 m/s	Nord (2020)
	Investment	2,500 US$/kW	IRENA (2016, 2020)
	O &M costs	40 US$/a	IRENA (2016)
Locally produced wind turbines	Rated power	18*1 kW	Kroeger (2020)
	Hub height	15 m	Kroeger (2020)
	Rotor radius	1 m	Kroeger (2020)
	Cut-in wind speed	2.5 m/s	Assumption
	Rated wind speed	6.8 m/s	Assumption
	Cut-out wind speed	16 m/s	Assumption
	Investment	1,500 US$/kW	Kroeger (2020)
	O &M costs	32 US$/a	IRENA (2016)
	Feed-in tariff	0.085 US$/kWh	Prime Minister (2018)
Battery storage	Capacity	46 kWh	Chaianong et al. (2020)
	Thereof utilizable	70 %	Hlal et al. (2019)
	Max. (dis-)charge power	20 kW	Assumption
	Efficiency	95 %	Kamath et al. (2020)
	Investment	209 US$/kWh	Kamath et al. (2020)
	O &M costs	0 US$/kWh*a	Kamath et al. (2020)
Second-life battery storage	Capacity	46 kWh	Assumption
	Thereof utilizable	60 %	Assumption
	Max. (dis-)charge power	20 kW	Assumption
	Efficiency	91 %	Kamath et al. (2020)
	Investment	65 US$/kWh	Kamath et al. (2020)
	O &M costs	0 US$/kWh*a	Kamath et al. (2020)

[a] Includes basic charge

[b] Due to missing data, only consider CO_2 are considered

the discounted initial investments, O &M and demand-related costs, as well as the

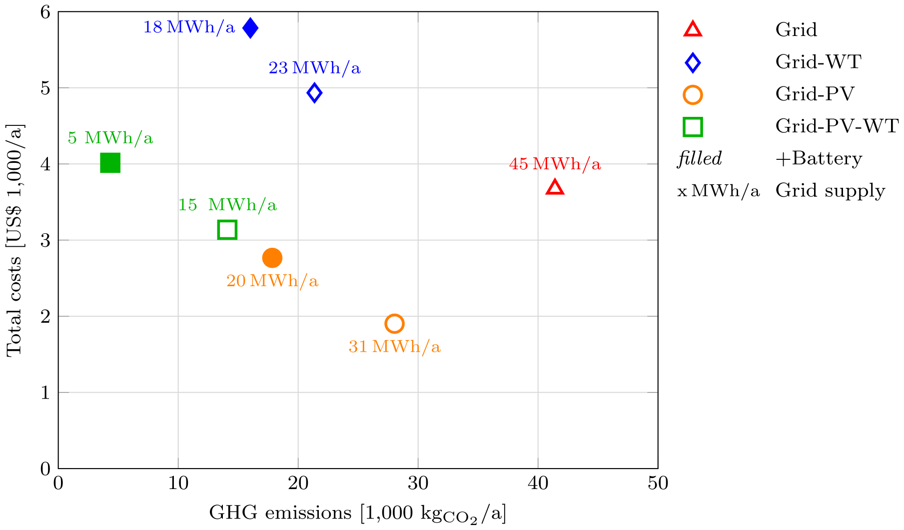


Fig. 7 Economic and ecological performance of analyzed energy system configurations for a representative neighborhood in Thua Thien-Hue, Vietnam

generated yields from selling surplus energy. The total costs in the reference scenario are 3,673 US$/a. More cost-effective are the three compositions Grid–PV, Grid–PV–WT, and Grid–PV–BS with cost reduction potentials of up to 50 % (Grid–PV). Considering the average annual household income of 4,653.52 US$/a, the share of electricity expenditures can be reduced from 2.6 % to 1.3 %. These results are driven by the high FITs that allow to sell excess generated energy. The Grid–WT–PV system, for instance, generates 70,684 kWh surplus energy per year. Due to the inherent characteristic of fluctuating yields of WTs and PVs, the energy cannot be put into productive use at all times. Thus, selling this surplus energy allows high monetary yields that reduce the RES investment and O &M costs. The RES Grid–WT–PV–BS, Grid–WT, and Grid–WT–BS increase the charges by 340 US$/a, 1,260 US$/a, and 2,112 US$/a, respectively. This is due to three factors: Firstly, the high investment costs of each WT and the additional BS. Secondly, the comparably high electricity costs from the central power grid due to the wind turbine's low efficiency. And closely related to this, the low yields through insufficient amounts of sold surplus energy.

Regarding the ecological impacts, most GHG are emitted in the reference scenario ($41,400\,kg_{CO_2}$) due to the grid's emission factor of $0.913\,kg_{CO_2}$/kWh. Since only RETs are considered, the lower the annual electricity purchase from the grid, the more environmentally friendly the system. The simulated RES show annual GHG emission reductions from $12,273\,kg_{CO_2}$/a (Grid–PV) to $27,317\,kg_{CO_2}$/a (Grid–WT–PV). Because BS increase a system's efficiency, the resulting decreased amounts of procured power lead to less GHG emissions for all compositions that include storage. Thus, the environmentally most advantageous RES is the Grid–PV–WT–BS combination with 4,749 kWh/a procured from the grid and annual GHG emission reductions of $37,073\,kg_{CO_2}$/a. Thus, this RES is capable of reducing annual emissions to 10%/a of the reference scenario's amount. However, this RES results in higher costs indicating a trade-off between the goals of economic viability and emission reductions. Despite the lower overall WT yield, the RES

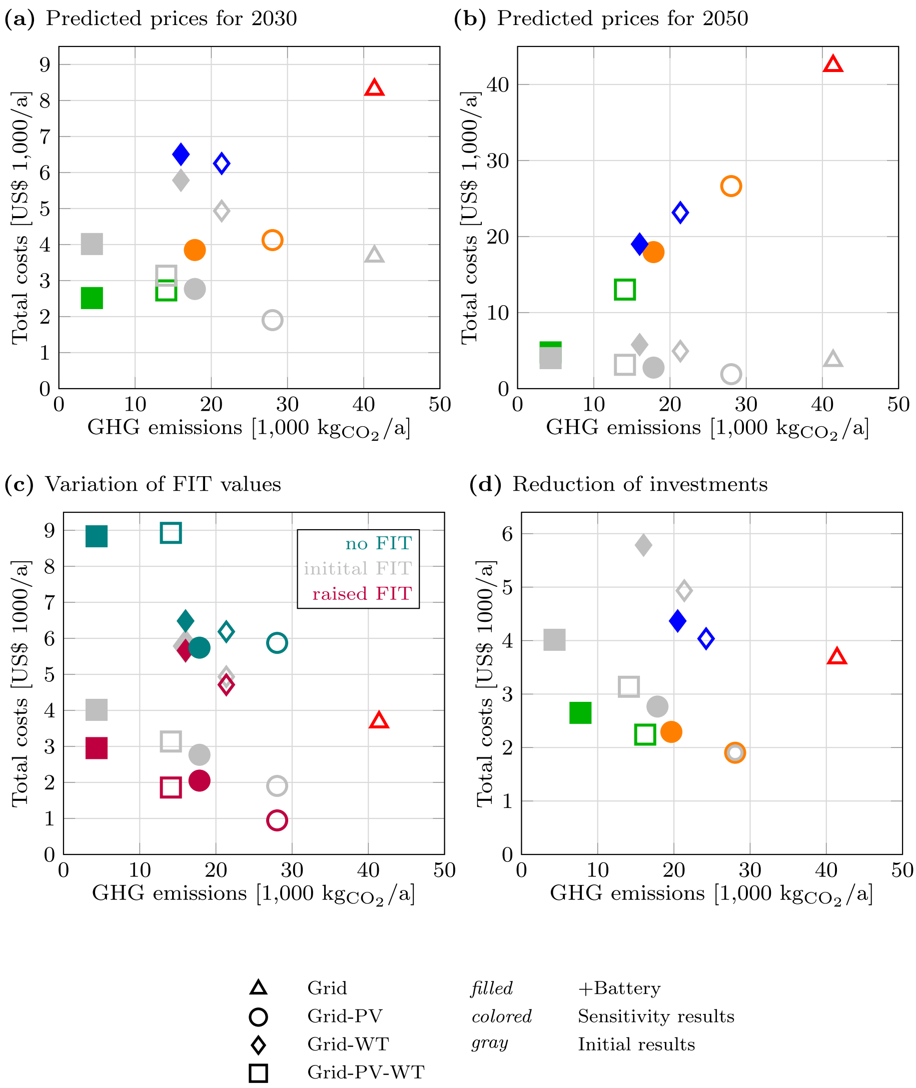


Fig. 8 Economic and ecological performance of energy systems of four sensitivity analyses

Grid–WT emits fewer GHG than the Grid–PV system. This suggests that the timing of wind yields matches the timing of demand better than solar yields. As a result, the positive impact of BS on GHG emissions is smaller in Grid–WT than Grid–PV RES.

The results of the sensitivity analyses are shown in Fig. 8. For a visual comparison, initial results are referenced in gray.

First, the predicted price developments for 2030 and 2050 are analyzed. The corresponding results are summarized in Fig. 8a and b, relating annual total costs to GHG emissions. In most cases, a large upward shifts in expenses is found. The reference scenario's costs rise to 8,304 US$/a in the year 2030, and successively increase to

42,462 US$/a in the year 2050. These results show the magnitude of monetary strains on electricity supply that can be expected in Vietnam in future. The cost reduction potentials with the application of RETs are now strongly dependent on the grid supply of each energy system. The higher the amount of electricity procured, the greater the cost difference from both the reference scenario and the 2020 values. For systems with strong dependencies on the power grid (Grid–PV, Grid–WT, Grid–PV–BS, Grid–PV–WT–BS), the savings from lower RET investments are not sufficient to offset the increased electricity costs from the grid. These systems are more cost-intensive in future. In contrast, systems with low electricity procurement (Grid–PV–WT and Grid–PV–WT–BS) show cost reductions in the year 2030 of 409 US$/a and 1,500 US$/a, respectively. Moreover, the combination Grid–WT–PV–BS enables cost stability in the year 2050 with relatively slight increases of 754 US$/a. The total annual costs of the latter RES are only a 10th of the costs for the reference scenario in the same year. These results strengthen the argument toward RET implementations to reduce the expected high cost of sufficient residential electrification in future. Generally, overall lower costs and emissions compared to the reference scenario are found. The earlier mentioned trade-off between economic viability and emission reductions shrinks as now the BS's positively influence both factors in the RES Grid–PV–WT. Figure 8b displays significant positive correlations in 2050, eliminating this trade-off completely.

In the following, the outcomes with varying FITs are compared. Figure 8c depicts the annual total costs and GHG emissions for the currently set FITs of 0.0806 US$/kWh (PV) and 0.085 US$/kWh (WT), no FITs, and increased FITs with values of 0.1 US$/kWh for both RETs. RES without FIT have higher costs than the reference scenario. The most expensive system is Grid–PV–WT with 8,927 US$/a, which was previously an economically viable composition. This exemplifies the FITs' influence on low total costs. For Grid–PV and Grid–PV–WT, BS are now not only ecologically but also economically advantageous compared to their counterparts without BS when no FITs are applied as they reduce the costs by up to 2,444 US$/a. The increased tariffs do not have a promising impact on Grid–WT and Grid–WT–BS compositions indicating further necessary incentives for the set-up of WTs such as investment subsidies. Nevertheless, with an additional BS the RES Grid–PV–WT becomes economically viable resulting in the most emission reducing and also more economically advantageous option than the sole grid supply. In comparison to the altered FIT levels, the current scheme is suitable to incentivize investments, generally, but should be increased slightly to motivate stakeholders to apply solutions with the highest emission reducing potentials.

Lastly, the potentials to reduce the amount of initial investments and, thus, the total costs per year are examined. The results are depicted in Fig. 8d. With locally produced WT and second-life batteries, the initial investments reduce by 17,500 US$/a (i.e., 27,000 US$/a) and 6,624 US$/a (i.e., 2,990 US$/a), respectively. Batteries have a significant positive effect on the system's efficiency. The RES Grid–WT, Grid–PV, and Grid–WT–PV procure 20 %, 40 %, and 70 % less electricity from the grid with additional BS. These systems also come with higher total costs of 800 US$/a–900 US$/a. This analysis depicts that the cost differences between BS including and non-including systems reduce by 300 US$/a–400 US$/a, leaving the investment in BS still economically disadvantageous—despite a price reduction of approximately 70 %. The cost cuts in WT through local production result in significant cost decreases for Grid–WT and Grid–WT–BS by up to 1,340 US$/a. However, compared to the reference scenario, these systems are still not cost competitive. Regarding the ecological changes, the lower efficiency of the systems resulted in an increase of GHG emissions by $1,824\,\mathrm{kg}_{\mathrm{CO}_2}$/a to $4,478\,\mathrm{kg}_{\mathrm{CO}_2}$/a. All economic results are

Table 3 Overview of economic simulation results

RES USD/a	Base	Price predictions (2030)	Price predictions (2050)	No FIT	Raised FIT	Reduced invest
Grid	3,673	8,304	42,462	3,673	3,673	3,673
Grid–PV	1,900	4,124	26,642	5,874	946	1,902
Grid–PV–BS	2,770	3,848	17,957	5,741	2,050	2,292
Grid–WT	4,934	6,252	23,158	6,186	4,713	4,036
Grid–WT–BS	5,785	6,505	19,002	6,483	5,662	4,367
Grid–PV–WT	3,136	2,727	13,028	8,927	1,859	2,241
Grid–PV–WT–BS	4,015	2,515	4,769	8,833	2,952	2,648

summarized in Table 3. For interested readers, further outcomes not included here can be found in the Online Resources, see Appendices B and C.

5.6 Interpret, infer, and recommend

In line with Nguyen (2007b), the results and findings show that with the current market structure and FIT value, most RES are ecologically and economically advantageous over the baseline scenario.

The use of RETs reduces electricity procurement which influences the indirect GHG emissions. In accordance, these results show significant ecological improvements in each RES with additional RETs and are validated by various research works, see, e.g., Nguyen et al. (2019a), Nguyen and Van (2021) or Nguyen (2007b). These changes are expected to elevate in future, as the rising electricity loads are currently met with imports and coal mining. These developments have lead to an increase of indirect emissions from 0.541 to 0.913 $\mathrm{kg_{CO_2}}$/kWh in the past 10 years and are expected to rise further (IGES, 2020). The associated negative environmental and health impacts, which often disproportionately affect the poor population, strengthen the argument toward the implementation of decentralized renewable energy. Regarding the rapidly increasing load demand, decentralized wind and solar energy solutions may be of particular interest for the Vietnamese stakeholders as their set-up generally takes less time than coal plant constructions, hydroelectric dams, or large-scale RES projects (Dapice, 2018, 2017).

Economically, RES are often advantageous due to income generation from the sold surplus energy and cost savings from grid supply reductions. Due to relatively low wind speeds at site, the WT's income through generating surplus energy does not cover their costs. Nguyen (2007b) validates these findings, but states that in areas with high wind speeds, WTs may be more economically and, thus, underlies the importance of location-specific simulations. Feeding-in electricity is also beneficial to relieve the national power grid and postpone necessary grid upgrades due to higher load requirements. However, high power feeds may also lead to grid overloads, which have already been observed in some regions of Vietnam (Nong et al., 2020). These risks will be reduced by higher self-consumption rates through, e.g., additional electrical appliances whose amounts typically increase with a newly available, reliable, and financially viable energy supply. Another option is the use of surplus electricity for electric mobility like cars, tuk-tuks or scooters, and heat generation, e.g., heat pumps and air conditioning.

RES can also decrease energy cost-induced poverty. With the current FIT policies, electricity costs can be reduced due to self-consumption and additionally generated income. However, the economically feasible energy systems require investments of up to 50 % of the annual income. These sudden costs would disproportionately affect other consumption goods and the household member's welfare. In line with Nguyen (2007b)'s findings and propositions, energy policies should be implemented that offer particular financial and technical support targeted toward the most disadvantaged population. The simulations do not include the cost of capital for loans. It is estimated that if the entire initial investment is financed over 20 years, an interest rate of 2 % must not be exceeded for individuals. Alternatively, the Vietnamese government could introduce subsidies to encourage investments. In any case, citizens need support in applying for subsidies and loans, as the financial literacy of the rural population in Vietnam is limited (Morgan & Trinh, 2017).

In the subsequent sensitivity analysis, it is observed that the expected price trends will increase the costs of most energy systems, although disproportionately. Energy-cost-induced poverty risks rise in future, however, the severance can be reduced by additional RETs. Tran et al. (2021) further validates these results stating that reduced RET prices will make isolated RES economically feasible—potentially even without governmental incentives.

FIT values have been successively increased in the past five years by the government. The second sensitivity analysis visualizes the importance of these tariff changes and shows promising effects for the current level. Lower FITs result in infeasible RES-including scenarios whereas higher FIT cannot decrease the system costs of the prior uneconomical scenarios to a satisfactory level. Several research set in Vietnam have not considered feed-in tariffs and validate our findings of RES being uneconomic without governmental incentives, see, e.g., Nguyen and Van (2021).

In contrast, the current electricity price is too low to encourage investments in RETs without corresponding monetary incentives. This is especially prominent for BS. With FITs and the electricity prices at a similar level, there are no economical incentives to purchase BS. The grid is able to function as a storage system with virtually no costs. As shown in the third sensitivity analysis, the costs of BS do not influence the investment decisions as grid usage is always more economical under current tariffs than BS investments. Thanh et al. (2021) validates these results, but argues that in light of deteriorating energy security, e.g., power grid failures, back-up batteries are useful and in some instances necessary.

Next to the economic and ecological sustainability analyzed in the simulation, social sustainability is an important, non-omittable factor for the long-term success of energy systems (Urmee & Md, 2016). Locally produced WTs are included to emphasize the importance of local value creation. The introduction of RETs results in local business opportunities through distribution, installation, and repair. The generation of new job prospects promotes knowledge transfers and skill developments through training in technical schools and companies. Comparing PVs and WTs, the creation of local employment is particularly strong when implementing the latter, as the installation, operation, and maintenance are mostly set in rural areas (Nguyen, 2007a). In conclusion, the slightly increased costs for systems without supporting PVs would still provide a promising application in future when considering the social factors and predicted price trends. It should be noted, that the use of second-life BS is also auspicious, but must be preceded by the formation of thoughtful regulatory frameworks clarifying the product's liability and capacity.

Based on the computational results and further validated by related literature, it becomes evident that the implementation of RETs does not only have promising long-term ecological, economic, and social benefits, but also decreases the risk of power grid overloads, localizes industries, and aids in poverty alleviation. Ultimately, the extent of the success of an economically viable, emission-reducing energy supply lies in the components' settings, prices, and market development. To formulate suitable policies promoting appropriate RES to residents in rural areas, it is advised that stakeholders conduct further analyses applying NESSI4D. In light of the SDGs, this work's implications do not only address Vietnamese interest groups but also international organizations and developed countries as the Vietnamese Government has limited financial resources (Nguyen et al., 2019c).

6 Evaluation, implications, and generalized recommendations

The artifact is evaluated through the demonstrating use case from Sect. 5 as is common in DSR Peffers et al. (2012) and DSS literature Arnott and Pervan (2012). The demonstration shows that the developed tool and process model are suitable for the intended application, i.e., the design of an RES under consideration of the location-specific energy situation in developing countries. Following step (i), all input data needed for NESSI4D is compiled or generated and the challenge framed. Missing data can be drawn from the tool's library or synthesized in detail with the help of the software RAMP. When the computations are conducted in step (ii), users are supported with numerous values and illustrative graphics provided by the software. With this tool, solution-oriented research on virtually all SDGs is enabled as called for by Leong et al. (2020), Gholami et al. (2016), and Walsham (2017). For instance, as NESSI4D provides renewable and traditional, fossil solutions, differences in GHG emissions are quantified and the advantages of renewable RETs highlighted, thus, supporting SDG 13 (climate protection), SDG 11 (sustainable cities), and SDG 3 (good health and well-being). SDG 7 calls for affordable energy, thus, NESSI4D carefully calculates the cost of energy systems to design governmental policies and avoid energy poverty which simultaneously tackles SDG 1 (end poverty). In step (iii) the user interprets, infers, and recommends about a suitable RES design with the given information. Using NESSI4D, household members and village leaders can factor numerous key values into their decisions, understand the impact of small changes, and design their customized optimal energy system. More broadly, policymakers are supported in forming site- and target-specific policy recommendations that align with national and international goals of feasibility, reliability, and emissions reductions. By empowering people to actively participate in the energy planning process, new potential is created, potentially leading to longer-term more successful projects and job creation, as Urmee and Md (2016) call for. Thus, NESSI4D contributes to practice as a measure to reduce complexities in the energy system planning process and to theory as a research tool. In summary, this work demonstrates the suitability of the tool-based method for performing structured analyses that include the most relevant indicators for energy system planning in developing countries.

In the demonstration, the software's results are validated with findings from related simulation research showing that energy systems powered by RES reduce environmental pollution and contribute to energy security, but must be financially supported through governmental incentives, see, e.g., Nguyen and Van (2021); Thanh et al. (2021); Tran et al. (2021); Nguyen et al. (2019a). However, this type of analysis is subject to the conflict between accuracy and generalizability, which means that transferring them to other energy projects should be done with caution. It is recommended to analyze each energy project individually with tools such as NESSI4D in order to achieve a long-term project success. Thus, the validation's expressiveness through comparison with other research literature is limited. Thus, the recommendations following the tool's results must be applied in practice and monitored in the long term. Thorough interviews should be conducted with experts in the fields of energy planning, development aid, construction, academic research, and private stakeholders to further validate and improve this work's approach.

7 Limitations and further research

The analyses show that this method allows stakeholders to support fundamental inferences about an optimal energy composition considering the circumstances and individual preferences of stakeholders. Regarding the input data, the usage of synthesized load profiles from survey data is sufficiently detailed to assess energy system configurations when data is scarce. Nonetheless, measuring load profiles at the site provides more precise results, as weekdays, vacations, and seasons were disregarded. In addition, the used survey was conducted in 2017. With energy demands rising by 8 % per year, results get outdated quickly. In its current version, NESSI4D does not account for demand increases. These must be considered in the energy system's final implementation to avoid the risk of undersized components. Further, NESSI4D solely accounts for emissions associated with energy flows whereas life cycle costs, including emissions during production and environmental risks due to poor waste management, are omitted. Knowledge of the component's operation, supervision, and repair, as well as accompanying technical capacities, also influences the long-term economic and ecological sustainability of an energy system. Besides, social sustainability is only discussed qualitatively but has been proven important for the long-term success of modern electrification projects (Urmee & Md, 2016). The omission of these factors may distort the results and findings.

Next to addressing the above-mentioned shortcomings, future research should conduct even more in-depth case studies using this or a further developed method. Regarding the case study, not all capabilities of the developed method have been showcased yet. The thermal infrastructure, as well as electric vehicles, have not been accounted for. The operation of the latter with excess energy, for instance, might enable an additional mode of affordable transportation that allows for better employment opportunities, time-efficiency increases, and health benefits due to decreased emissions. Further research examining buildings beyond the residential sector such as schools or administration offices can also prove beneficial, provided corresponding data can be obtained. On the subject of NESSI4D, the inclusion of additional renewable energies such as biomass, hydro, or hydrogen and incorporation of load evolution will be future tasks. The ultimate objective is to develop a comprehensive decision support system for politicians and building owners in developing countries to make informed decisions about their energy systems. The research goals, therefore, overlap with the academic field labeled ICT4D where Walsham (2017) identified environment and climate change as major societal issues that must be addressed with information and communication technology. The authors aim to make NESSI4D available for said stakeholders in future via a web application.

8 Conclusions

Rapidly rising energy demands, depleting fossil fuels, and the aim for an ecologically, economically, and socially more sustainable energy system motivate stakeholders to rethink energy infrastructures for buildings and small, decentralized energy networks. The lack of information, data, and local expertise is a major challenge for the future wide-spread use of renewable energy in developing countries. Following the call for inter-disciplinary, solution-oriented research, a tool-based method to enable multi-energy planning considering location-specific circumstances is developed. Following a DSR approach, the energy system simulation tool NESSI is adapted to address stakeholders' needs in developing countries. To further reduce complexities, a detailed process model is provided as a manual for energy system planning with simulation models. As common in DSR and DSS research, the applicability of the approach is then evaluated and validated with a demonstrating use case. Following the demand for scientific energy research in Vietnam, a case study for a representative village of thirty rural poor households in the Thua Thien-Hue province is conducted. For this purpose, load profiles evaluated from detailed household survey data and synthesized with RAMP are used. It is found that the implementation of PV modules and WTs is more economically, environmentally, and socially sustainable than sole grid utilization. Predicted price trends depict cost increases for electrification and higher risk for energy-cost induced poverty reinforcing the need for the promotion of renewable components. The demonstration shows the importance of careful policy planning when setting incentives such as feed-in tariffs and cost reduction potentials through second-life batteries and locally produced wind turbines. Investments in RES are suitable for poverty alleviation, job creation, and industry localization for the rural population in Vietnam. It is recommended to promote RETs in rural areas, formulate tailored energy policies, and support local stakeholders to facilitate the transition to modern electrification. The demonstrating case study validates the artifact's relevance and emphasized the importance of providing highly specified DSS tools for energy system planning in developing countries. Thus, NESSI4D contributes to practice as a measure to meet the SDGs and to theory as a research tool and must be further improved in future works.

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Availability of data and material All supplementary data can be viewed in the file named "Online Supplements." For information about the raw survey data, please, contact the authors.

Code availability The software is not open-source yet, but an open-access web-application is being programmed at the moment. We provide screenshots of our analysis in our Online Resources.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Informed consent was obtained from all authors.

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