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

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Abstract

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

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

1. Introduction

In the past decades, governments and development aid agencies have been focusing on providing rural areas in developing countries with reliable, affordable, sustainable, and modern energy (i.e. Sustainable Development Goal (SDG) 7), as it is a key factor to improve living conditions and promote social development (Herraiz-Cañete et al., 2022). Due to their modularity and cost-effectiveness, decentralized renewable energy systems (RESs) have a significant positive impact on these efforts (Balderrama et al., 2020; Few et al., 2022; Herraiz-Cañete et al., 2022). However, selecting and sizing renewable energy technologies (RETs) is challenging (Balderrama et al., 2020). Technical knowledge, the vast amount of needed - but often missing - information, and location-specific characteristics, are prerequisites for RES planning. Therefore, energy system analyses are often conducted using decision support systems such as HOMER, iHoga, or NESSI to facilitate the decision process towards suitable RES and the formulation of energy policies. In addition to site-specific factors, human capital, and market data, expected energy demand has significant impact on the RES' design (Herraiz-Cañete et al., 2022). The magnitude of energy demand, specifically the often observed demand peaks, determines the RETs' size and capacities (Few et al., 2022). Oversizing RETs, as is common in developed countries, increases investment, operation and maintenance (O&M) costs without commensurating benefits (Herraiz-Cañete et al., 2022). Undersizing leads to unreliable supply, stakeholder dissatisfaction, and avoidable use of harmful fossil fuels (Few et al., 2022). The temporal distribution of electricity demand determines the balance between energy generation, distribution, and storage and affects their intricate relation (Few et al., 2022). As detailed demand data is regularly missing or inaccessible, this critical factor is often only roughly estimated in energy system simulations and rural electrification research, leaving out local conditions, temporal variations, and uncertainties. Recent studies have shown that load profiles are neither easily predictable nor modeled, as people's electrical appliance usage patterns vary depending on their schedules and lifestyles (Proedrou, 2021). The independence of energy system simulation and load profile generation tools further impedes the process. Related tools often do not reflect the desired level of detail, are not open-source, or require programming knowledge (see Section 2), which increases the likelihood of inaccessibility or unsuitable load profiles. We, thus, use a user-centric approach and conduct a design science research process according to Peffers et al. (2007) to combine tools for energy system simulation and load profile generation. More precisely, we implement the open-source multi-energy

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load profile generator RAMP by Lombardi et al. (2019) into our previously developed web-based energy system simulator NESSI (Eckhoff et al., 2022; Kraschewski et al., 2020). In addition to our solution-oriented, practical contribution, our research advances theory by providing a research tool that accounts for the necessity of accessible load profile synthesis in developing countries and enables the conduction of detailed, in-depth case studies. After an overview of related software (Section 2), we present our research design and methods in Section 3. The design and development of the artifact are described in Section 4. We present the results of an applicability check with self-collected data in Sri Lanka in Section 5, before discussing the tool's implications and limitations in Sections 6 and 7. Finally, we conclude the study in Section 8.

2. Related software

The most popular energy system simulation tool that includes load profile generation is the commercial software HOMER Pro (link). It allows to import U.S.-American facility profiles from the OpenEI database. The developers advise selecting profiles that have similar climatic conditions to the ones at site and apply a similarity measure based on the Koeppen Geiger Climate Classification Index (HOMER Energy LLC, 2022). The tool further enables users to expand typical daily to annual load profiles by considering randomness factors. Other tools, such as iHoga (link), Hybrid2 (link), and our tool NESSI (link), allow to import hourly and average user load data or offer predefined load profiles (Baring-Gould, 1996; Dufo López, 2022; Eckhoff et al., 2022). However, these approaches are not sufficient in the context of rural areas in developing economies as the people's living conditions differ considerably from those in industrial countries. Expanding or averaging load profiles is not appropriate because they are regularly nonexisting, do not adequately reflect reality, or are outdated. Pre-defined load profiles are also often unsuitable as demands are characterized by high volatility and changes in the future due to, e.g., the surge in electrical appliance ownership and changing social conditions (Proedrou, 2021). Therefore, researchers have been using tools specifically designed to synthesize missing load profiles. In general, these tools are grouped into deterministic and stochastic prediction approaches. The former assumes exact relationships among variables and uses methods such as neural networks, regression trees, or multiple linear regression models. In contrast, the latter considers randomness of variables. Despite the high usability and rigidity of deterministic models, stochastic models are recommended as they produce more accurate results (Herraiz-Cañete et al., 2022). A second recommendation in terms of load profile generation is the bottom-up approach, i.e. the collection and analysis of individual consumer data and their subsequent extrapolation (Proedrou, 2021). Proedrou (2021) identifies the advantages of this approach as high accuracy of results, suitability for analyzing the impact of technologies, policy decisions, and energy optimization as well as independence of historical data. In the literature, several stochastic bottom-up modeling approaches are presented, see Lombardi et al. (2019) for a comprehensive overview. They are fed with data from detailed activity diaries, national time-use surveys, precise power profiles per appliance as well as device ownership statistics. Most approaches are context-specific to particular cases in developed countries and urban areas. For rural areas in developing countries, however, an approach is needed that can cope with the settings at site, inexact data, and is readily available for stakeholders. One possibility is the commercial software Demand Analyst© (link) by the Innvoation Énergie Développement (IED) of France. The software estimates annual consumption, energy peaks, and daily load demand of village clusters including residential buildings, public services, and economic activities with survey data and regional socio-economic parameters (Innvoation Énergie Développement, n.d.). Although already used in multiple developing countries, its commercial nature indicates a high, often insurmountable cost barrier. Open-source tools include ESCoBox (link) and RAMP (link). Applying the central limit theorem, ESCoBox predicts daily peak and average electricity demand from information on consumers and their hourly appliance usage behavior (Boait et al., 2015). The tool can be combined with a hardware element that limits electric power to specific time windows and is, thus, suitable for mini- or micro-grid operators to formulate control strategies and price structures (De Montfort University, 2022). RAMP synthesizes minutely multi-energy load profiles and employs a high degree of stochasticity to multiple parameters that relate to appliance characteristics and consumers usage behavior, e.g., number of appliances, power utility as well as frequency, duration, and windows of use (Lombardi et al., 2019). The software was specifically designed to generate high-resolution load profiles in developing countries and is considered one of the most complete and functional tools of flexibility and customizability (Clements et al., 2021; Herraiz-Cañete et al., 2022). However, although open-source, the tool lacks accessibility as it does not have an interface

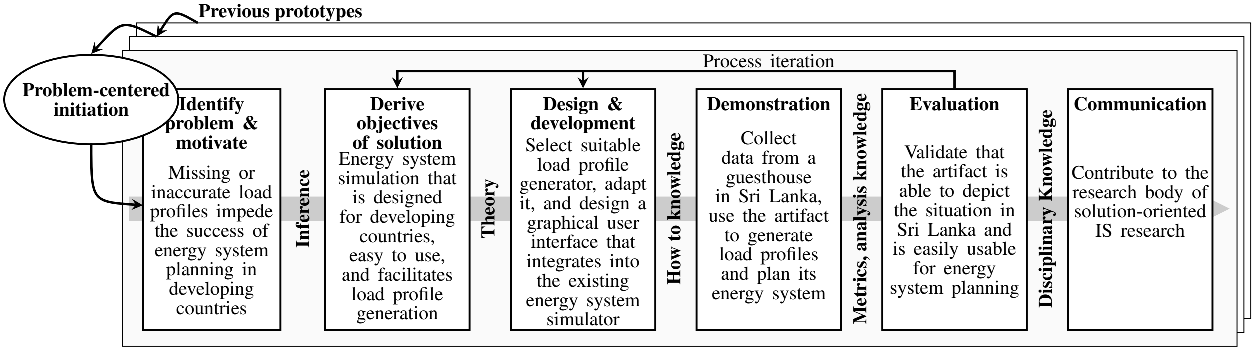


Figure 1. Design science research methodology adapted from Peffers et al. (2007).

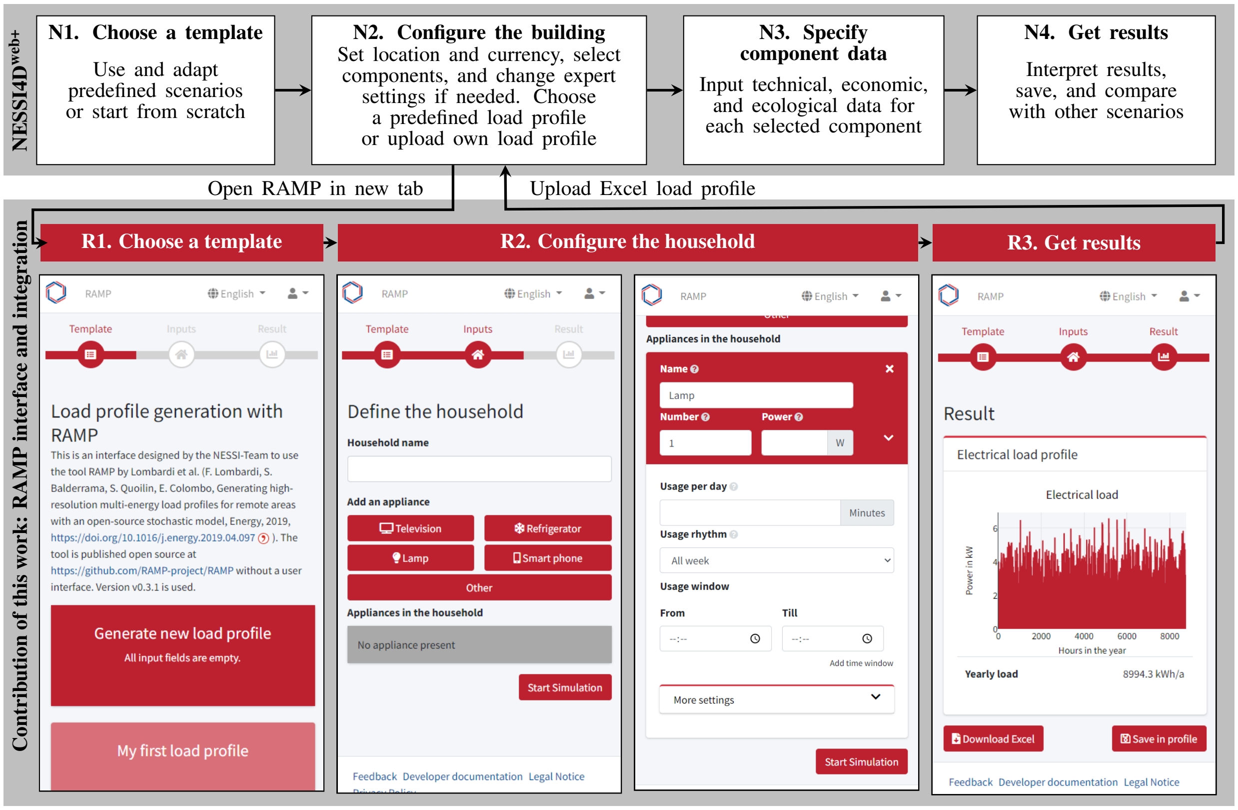
and requires programming knowledge. Additionally, all presented tools are independent of energy system simulators. Energy planners first have to conduct in-depth research or training to use these tools and often fall back to easier approximation methods whose detriments are outlined above. Thus, we conclude that we have not found an accessible approach of high usability for stakeholders in developing countries to design rural RES comprehensibly and accurately.

3. Research design

We follow the calls within the Information Systems (IS) community for solution-oriented, user-centric research (Lehnhoff et al., 2021) and develop an artifact that facilitates accessible load profile generation during RES planning. With the energy system simulator NESSI4D^{web+} (NESSI for short) as the basis, we apply the design-science-oriented approach by Peffers et al. (2007) shown in Fig. 1 to improve the software. The development of NESSI4D, originating from NESSI by Kraschewski et al. (2020), was motivated by the lack of adequate decision support for energy system planners in developing countries. To account for time variations whose consideration is also imperative in terms of electricity demands, multi-year analyses were integrated in a second design cycle (NESSI4D^{+}) (Eckhoff et al., 2022). For increased accessibility, the tool was re-calibrated as an open-access web tool that is usable on various devices in a third cycle (NESSI4D^{web+}). The initiation of this fourth design cycle, which is the subject of this work, is problem-centered and derived from the evaluation of the previous prototypes with experts from developing countries. During the interviews, we received feedback that the synthesis of load profiles on NESSI4D^{web+}'s website is an important feature to improve RES planning in developing countries. It was specifically requested that users of the software should be able to easily create customized load profiles according to their requirements and circumstances. As outlined above, this need is confirmed in the scientific literature. We found no other tool that offers the required functionality of detailed load profile generation with an intuitive graphical user interface that is suitable for developing countries. We chose the tool RAMP for our new load profile generation module because it is highly regarded for its completeness, flexibility, and suitability in developing country contexts (Clements et al., 2021; Herraiz-Cañete et al., 2022). Thus, in the design and development stage, we expanded the graphical user interface of NESSI4D^{web+} by pages that enable load profile generation with this software. The detailed functionality and changes are described in Section 4. Subsequently, we conducted an applicability check to evaluate and validate the efficacy and utility as is common in design science research (Peffers et al., 2012) and decision support system literature (Arnott & Pervan, 2012). For this purpose, we chose an appropriate context to demonstrate the functionality of the prototype and discuss whether it is usable and includes the required settings. Thus, in line with Lehnhoff et al. (2021) who emphasize that IS research does not have to be theory-building at once, but must provide solutions for practical applications, we contribute to the research body of solution-oriented IS research and provide a research tool for energy system planning in developing countries.

4. Artifact description: Energy system planning with detailed load information

Our energy system simulator NESSI4D^{web+}, which stands for **N**ano **E**nergy **S**ystem **Si**mulator for **D**evelopment, is an open-access web tool that is available at https://nessi.iwi.uni-hannover.de/en. It is programmed in Python 3.9 using the web framework Django (link). NESSI simulates hourly electrical



Load profile generation with RAMP

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

Name: Lamp

Number: 1

Result

Yearly load 8994.3 kWh/a

Figure 2. Graphical user interface and user flow integration of RAMP into NESSI4D^{web+}.

and thermal energy flows in buildings and quarters with a ranking-based energy management. Energy system components comprise a variety of thermal and electrical energy generating and consuming technologies. Loads are aggregated at the building or neighborhood level and covered by the selected components of that infrastructure in a predetermined order. For the calculation of the photovoltaic systems' and wind turbines' yields, NASA Merra-2 weather data is used. In general, usability is a focus point of NESSI's development. This is facilitated through a cohesive, clear design of the user interface. Predefined scenarios are offered as templates and a progress bar is used to guide users through the simulation steps. NESSI can be used without registration, but a (free-of-charge) user account is necessary for saving, comparing, and sharing scenarios. NESSI is adaptable to all screen sizes and provides help texts for all input fields. While simulating energy system scenarios, users can choose pre-generated residential and commercial load profiles. Alternatively, demand data can be uploaded if no load profile fits the user's needs. In previous case studies (see, e.g., Eckhoff et al. (2022)), we generated load profiles separately via the RAMP script and uploaded them to NESSI afterward. To keep the independence of RAMP, this workflow is maintained. However, to meet the calls for more accessible and usable load profile generation in practice and literature, we have added the following new features and modifications: The functionalities of RAMP v0.3.1 are added as a standalone application and are made available as a sub-site of NESSI (link). The sub-site is linked at NESSI's step where a load profile can be uploaded and opens in a new tab. The resulting user flow of the combined tools is depicted in Fig. 2.

To enable control of RAMP via a web interface, the process of passing input data to the simulation kernel had to be modified. Instead of manually generated input files, a Python dictionary is generated from input on the web page and passed to RAMP. For simplicity, all appliances are assigned to one user instance. In RAMP, the number of day profiles is queried via the command line. In NESSI-RAMP, we hard-coded that 365 day profiles are to be created. Apart from these changes, RAMP is used as developed by Lombardi et al. (2019). The included post-processing functions to generate plots and result files are not used. To obtain the hourly annual load profile in Kilowatts that NESSI requires as input, a self-written post-processing script converts the 365 load profiles available in minute-by-minute resolution and Watts to the correct format.

The new graphical user interface is also depicted in Fig. 2. On the start page, the user is able to select from templates (both public and, if applicable, previously saved by the user) or start from scratch. On the second page information on appliance usage and behavior is queried: First, the user defines the name of the load profile. Subsequently, the user either selects pre-defined electrical devices, whose characteristics can be flexibly adapted or defines their own appliances. For each appliance, it queries the number in the building as well as the power consumption. Subsequently, the daily usage time in minutes, the usage rhythm per week, and the usage time windows are entered in the standard queries. In pre-filled expanded settings, the user can modify the variability of the time windows, the probability of daily use, randomization parameters, and the minimum duration of use after switching on the appliance. After starting the simulation, the resulting load profile is presented graphically and the option of download in Excel format is given. In the intended workflow, the user downloads the load profile directly, closes the tab, and uploads the load profile in the still open NESSI4D$^{\text{web+}}$ tab. Additionally, the user can save the load profile in their NESSI user profile for later download and re-use as a template.

For high usability, but obvious distinction, the website is designed in a similar style to NESSI4D$^{\text{web+}}$, but using red instead of blue as the primary design color. As a recurring design element, a progress bar is used to guide the user through the simulation. Again, help texts are used to provide further assistance. On the start page of NESSI-RAMP, we explicitly link to the original RAMP paper and repository and mention which version of RAMP we are using. On the input page, each device is delimited as a separate container. The containers for all devices can be collapsed. In their collapsed state, only the input fields number, name, and power are shown. When the user edits one device, all other device containers collapse to avoid confusion. The generated load profile is displayed in an interactive graphic that allows zooming and panning so that the user can interact with the plot.

5. Evaluation: Applicability check in rural Sri Lanka

5.1. Energy situation and scenario data

In 2022, high inflation and the depletion of foreign reserves resulted in Sri Lanka's inability to buy essential goods, leading to shortages of food, medicine, and gas (Sharma et al., 2022). As a consequence of the high dependence of the energy sector on imported fuels and the inability to pay for them, electricity availability is degrading resulting in daily power outages (CEB, 2022b; Herath & Jung, 2021). Given the government's commitment to reduce greenhouse gas emissions, increase the share of renewable energy generation, and reduce dependencies, decentralized systems offer a suitable solution (Balderrama et al., 2020; Danthurebandara & Rajapaksha, 2019; Few et al., 2022; Herraiz-Cañete et al., 2022). Researchers analyzing Sri Lanka's energy sector often use outdated or constant daily load profiles, estimates from the literature, or refer to urban areas, industries, or the entire country (Athukorala et al., 2019; Fernando et al., 2019; Jayasinghe et al., 2018; Silva et al., 2018). However, especially due to increasing electricity consumption, changes in demand patterns, industrialization, and modernization, detailed load profiles are crucial for proper RES planning in the country (Athukorala et al., 2019; Herath & Jung, 2021; Jayasinghe et al., 2018).

We have conducted interviews with Sri Lankan guesthouse owners and selected one guesthouse for this applicability check. The guesthouse is used by its residents as well as tourists. Missing information is filled with assumptions, e.g., from Lombardi et al. (2019) and Sardima et al. (2021). The guesthouse is assumed to be fully booked with two occupants per room. The assumptions of the assets' usage are dependent on the average time between sunrise and sunset, assumed working hours, and free-time behaviors. For simplicity, weekends, vacation days, as well as the differentiation between seasons, are omitted. The appliance ownership and usage behavior of the guesthouse are summarized in Tab. 1. First, we analyze the impact of the load profiles' distribution by comparing constant demand with a load profile generated with RAMP. Second, to show the effects of demand magnitude, we add air conditioners in a second scenario as they are commonly requested by tourists and desired by guesthouse owners. For each load profile assumption, we design RESs in NESSI4D$^{\text{web+}}$ and compare the results with traditional solutions. For the RESs, we choose a photovoltaic system due to the country's high solar irradiation and a battery storage due to its ability to smooth periodic electricity generation (Herath & Jung, 2021). For the traditional energy system, we include a diesel generator as it has become common in Sri Lanka as a backup generator to circumvent the frequently occurring power outages. The size of the components is determined individually. All components are newly purchased at the beginning of

Table 1. Assumptions of appliance ownership and usage of a guesthouse in Sri Lanka.

Appliance	No.	Power [W]	Min. run time [min/day]	Total run time[a,b,c] [min/day]	Usage window 1[d]	Usage window 2[d]
Guestroom (2x)						
Outdoor light bulb	3	13	60	270	05:30-06:00	18:30-22:00
Indoor light bulb	6	7	30	120	05:30-06:00	18:30-23:59
Shower heater	1	3500	10	20	07:00-10:00	19:00-22:00
Kettle	1	1500	5	10	07:00-10:00	19:00-22:00
Hair dryer	1	1500	10	10	07:00-10:00	19:00-22:00
Smartphone	2	5	120	120	00:00-10:00	18:30-23:59
Camera	1	5	120	120	00:00-10:00	18:30-23:59
Power bank	2	15	300	300	00:00-10:00	18:30-23:59
Laptop	1	15	120	120	00:00-10:00	18:30-23:59
Air conditioner	1	1500	15	420	00:00-09:00	19:00-23:59
Attached residential home (1x)						
Outdoor light bulb	2	13	10	120	05:30-06:00	18:30-23:59
Indoor light bulb	3	7	30	300	05:30-06:00	18:30-23:59
Shower heater	1	3500	10	30	05:30-07:30	18:30-23:59
TV incl. satellite dish	1	75	30	240	05:30-07:30	18:30-23:59
Radio	1	7	10	240	05:30-07:30	18:30-23:59
Refrigerator	1	150	10	240	00:00-23:59	-
Kettle	1	1500	5	20	05:30-10:00	18:30-21:00
Blender	1	300	5	10	05:30-10:00	18:30-21:00
Rice cooker	1	1400	30	60	05:30-10:00	18:30-21:00
Smartphones	3	5	120	120	00:00-07:30	18:30-23:59
Washing machine	1	500	45	45	05:30-22:30	-
Iron	1	2300	20	20	05:30-22:30	-
Fan	2	55	240	480	00:00-07:30	18:30-23:59
Toaster	1	800	5	10	07:00-10:00	18:30-22:30

[a] Total time of use that is subject to random variability: 10 %
[b] Usage rhythm: All week
[c] Probability the the appliance is used daily: 100 %
[d] Variability in the start and ending times of windows: 35 %

the project. We include the planned power interruptions of the central power grid in Sri Lanka and incorporate outages of 5 hours every 20 hours (CEB, 2022a). We assume a project duration of 20 years and a discount rate of 9 % (ADB, 2017). All technical, economic, and ecological input data for the RETs is shown in Tab. 2.

5.2. Results and findings

Using RAMP's new interface, we generate the guesthouse's load profile whose load amounts to 3,500 kWh/a. Additionally including two air conditioners increases the demand to 8,970 kWh/a. The hourly load profiles are depicted in Fig. 3 for the whole year (8,760 h) and two random days thereof (i.e. 48 h). We observe the volatility of demand due to the predefined time windows, additional uncertainty, and stochastic parameters. Peak loads are observed in the morning and evening, which correlates with the imputed assumptions. Additional air conditioners increase the demand especially during peak times. Further, a constant load of 0.4 kW is depicted which equals the yearly load of our collected appliance data, i.e. 3,500 kWh/a.

The differences in load distribution and magnitude have a considerable effect on the energy system. We compare sole grid connection with the traditional solution of a supporting diesel generator (2.5 kW), a RES, i.e. photovoltaic system (3.5 kW) and battery storage (8 kW), and a hybrid solution with both RETs and a smaller backup diesel generator (1 kW). With the given specifications, the photovoltaic system generates 4,460 kWh/a. The investment at the beginning of the project is 1,250 US$ for the traditional solution, 4,470 US$ for the RES, and 4,970 US$ for the hybrid system.

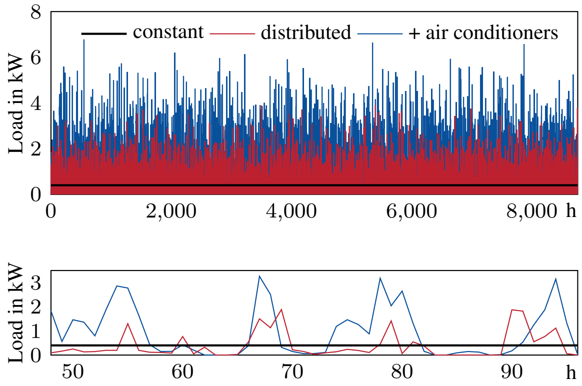


Figure 3. Load profiles of the exemplary guesthouse.

In terms of electricity supply reliability, we observe that a quarter of the electricity demand is not met by sole consumption from the central power grid due to the planned power outages. RETs reduce the uncovered load to 1 % and additional diesel generators provide

Table 2. Input data and technical settings for the guesthouse in Sri Lanka.

Component	Input	Value	Based on
Central power grid (CPG)	Electricity price	0.062 US$/kWh	CEB (2022b)
	Outage cycle & duration	20 h & 5 h	CEB (2022a)
	Emission factor	$0.646\,\mathrm{kg}_{\mathrm{CO_2\text{-eq.}}}/\mathrm{kWh}$	EIB (2022)
Photovoltaic system[a] (PV)	Efficiency	20 %	Assumption
	Performance factor	70%	Assumption
	Orientation	South	Jacobson and Jadhav (2018)
	Tilt angle	10 °	Jacobson and Jadhav (2018)
	Investment	$800\,\mathrm{US\$/kW}_{peak}$	IRENA (2020)
	O&M costs	$9.5\,\mathrm{US\$/kW}_{peak}\mathrm{*a}$	IRENA (2020)
Diesel generator[a] (DG)	Minimum load ratio	30 %	Kamath et al. (2020)
	Efficiency	26 %	Aberilla et al. (2019)
	Investment	500 US$/kW	Silva et al. (2018)
	O&M costs	30 US$/(kW*a)	Assumption
	Fuel costs	1.105 US$/l	Valev (2022)
	GHG emissions	$0.267\,\mathrm{kg}_{\mathrm{CO_2\text{-eq.}}}/\mathrm{kWh}$	GOV.UK (2017)
Battery storage [a] (BS)	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)

[a] Lifetime 20 years.

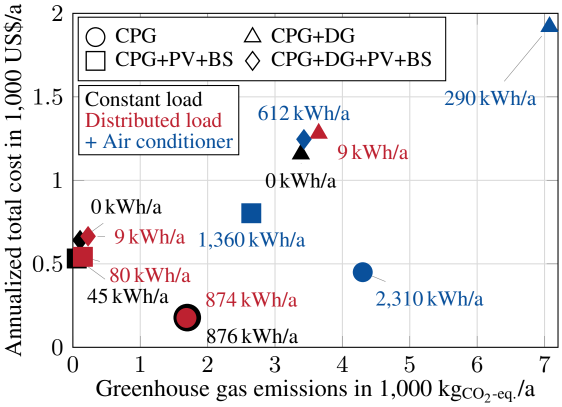


Figure 4. Energy supply scenarios for the exemplary guesthouse (uncovered loads depicted as labels).

reliable supply. When using the distributed load profile, the uncovered load in the RES increases. This is due to two factors: First, central power grid power outages occur during peak periods. Second, electricity is demanded at times when it is not generated. Therefore, larger battery storage or backup generators are required. The inclusion of air conditioning significantly increases the uncovered load in all scenarios, indicating that the RETs, battery storage, and diesel generator are undersized.

Regarding the economic dimension, we find that sole grid connection is the cheapest option due to low electricity prices. Although high in initial investment, the RES and hybrid solutions are more economical with total costs of 500 US$/a to 1,200 US$/a than an additional diesel generator with 1,200 US$/a to 1,900 US$/a depending on the underlying assumptions. Load variations specifically affect systems that include diesel generators, indicating that power outages often occur during peak demand periods and the cost of RETs is independent of their utilization. The impact of increasing demand magnitude depends on the availability of a diesel generator, which is driven by high diesel fuel costs that directly correlate with diesel generator operating hours. In contrast, although consumption from the central power grid increases, the impact on costs remains small. These effects are expected to exaggerate in the future with rising diesel fuel costs and inflation.

Even though electricity consumption from the central power grid is the most economical solution and the traditional solution the most reliable, their local emissions are up to 60 times higher than from systems including RETs. Similar to the reasoning of the economic impacts, the ecological footprint of the energy systems depends on the utilization of the central power grid and diesel generator. Hence, load distribution and magnitude elevate emissions, however, systems including RETs are the most ecological across assumptions and scenarios.

As Sri Lanka suffers energy security and dependency challenges, energy systems with a high degree of autarchy are preferable. Specifically due to the prevalent diesel scarcity and unreliable central power grid supply, alternative resources independent of socio-economic and political circumstances are of interest. Detailed load profiles are needed as undersized systems do not generate enough electricity resulting in dependencies on traditional solutions. We observe these effects specifically in systems with RETs as the degree of autarchy decreases from 95 % to 50 % when including air conditioners. Additionally, the local markets need to be considered as spare parts and repair services must be readily available for all used RETs.

In conclusion, we find that the load profile's distribution and magnitude have considerable effects on the dimensions economic viability, ecological sustainability, energy security and dependency of the energy systems. Generally, systems including RETs have positive effects on these goals, but diesel generators are a viable solution to secure a reliable supply during peak demands, uncertainties, and supply shocks.

6. Discussion, implications, and recommendations

During data collection of several guesthouses in Sri Lanka, we have found that appliance ownership and desires vary greatly between rural guesthouses, stressing the need for non-standard, topical, and detailed load profiles. Our applicability check in turn validates that costs, emissions, and load coverage ratios are heavily impacted by load assumptions.

As we conducted several case studies in the past using RAMP, we conclude that its usability improved considerably through the provision of a web interface. By coupling with our energy system simulator, the time required to produce the energy system simulation results is significantly reduced. Of particular importance is that no programming knowledge or downloads of the script and Python software is required. In addition, the input fields are labeled, which eases the process of entering data. In the original version, it is often necessary to navigate between the input file and the core script to inquire about the meaning of variable names or the correct order of input. Through the interface, we further facilitate imputing data in commonly used format, e.g., times of day instead of the conversion into minutes. Finally, the load profiles immediately have the correct format (hourly and in kW) for the upload into NESSI.

In general, tools like NESSI4D^{web+} that focus on usability for all stakeholders, empower decision-makers by facilitating the planning process of decentralized RESs, raising awareness of the economic, ecological, and reliability impacts of RETs, and supporting the formulation of data-based policies. With NESSI4D^{web+} we aim to support the United Nations' SDGs, especially SDG 7 (affordable and clean energy) and SDG 13 (climate action) bottom-up and with a focus on stakeholders in developing countries. Such tools must be available to all stakeholders and the resulting decisions made collaboratively. Thereby, individual goals and needs are included and data-driven strategies developed. Simultaneously, decisions based on secondary information from third parties are avoided. Due to the different energy markets, local characteristics, and uncertainties, we emphasize the importance of various in-depth simulations and analyses with NESSI4D^{web+}. The impact of NESSI4D^{web+} is significantly improved through the inclusion of the load profile generation tool RAMP. Users are empowered to analyze the impact of additional appliance purchases, fostering environmental awareness by highlighting the impact of appliances with high demand such as air conditioners (see applicability check). The effects of behavioral changes in appliance usage are directly observable, potentially fostering efficiency-increasing activities or decreasing total consumption. These decision freedoms and analyses can highlight the impact of energy consumption, provide transparency of processes and decisions in energy projects, and thus generate higher trust among stakeholders. Thus, we have validated our approach and recommend the dissemination and usage of our artifact both in research and practice as it provides a sufficient level of detail for academic case studies combined with usability suitable for non-expert use.

7. Limitations and further research

Our applicability check is subject to several assumptions. For more validity, further detailed data needs to be collected. However, this does not limit the software's functionality as users are able to impute their own information. We omitted some functionalities of RAMP for its web version to keep the application as usable as possible. For example, RAMP provides the opportunity to insert specific cycles in which appliances are used and power curves of appliances instead of a constant value. In future research, further evaluations with experts should be conducted to detect opportunities for complexity reduction while maintaining high usability and realistic results. Features that were omitted in this development process could then be implemented. The software's usability decreases with the number of appliances owned as information for each has to be inserted separately. Further research should focus on simplifying this process through, e.g., templates. Further, RAMP's branch with additional multi-year functionalities (link) allows simulating the additional acquisition of appliances over a longer period as is common after access to more reliable electrification. Similarly, NESSI is able to simulate multiple years to allow for time variations (Eckhoff et al., 2022). Nevertheless, this feature was not adopted for the artifact, as the computing time for common project lengths of 10-20 years amounts up to several hours. Future research should resolve this issue for an increased level of detail.

8. Conclusions

Successful energy system planning is dependent on detailed electricity demand information. Especially in developing countries, pre-generated load profiles are often unsuitable as appliance ownership and usage vary significantly across borders, between urban and rural areas, and on household and industry levels. We found no tool to synthesize individual load profiles that provides the required level of detail, is freely and easily accessible, and comprehensible. Therefore, we applied a design science research process to design a user interface for the open-source load profile generator RAMP. To ease the workflow of energy system planning, the interface was included in our open-access web-based energy system simulator NESSI4D^{web+}. We conducted an applicability check with self-collected data from a guesthouse in Sri Lanka, comparing the impact of different details of load profiles and of additional appliances on the economic, environmental, reliable, and secure energy supply. It validated the artifact's relevance and emphasized the importance of providing accessible detailed load profile generation for energy system planning in developing countries to empower local decision-makers.

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