Assessment of Microgrid Potential in Southeast Asia Based on the Application of Geospatial and Microgrid Simulation and Planning Tools

Paul Bertheau, Martha M. Hoffmann, Andrea Eras-Almeida and Philipp Blechinger

Abstract Enabling access to energy is crucial for achieving the sustainable development goals (SDGs). A particular challenge for countries in Southeast Asia is to develop sustainable energy systems on their far-flung islands to increase energy security and improve living conditions. Here, renewable energy microgrids combined with other emerging energy technologies hold a large potential for sustainable remote-area electrification. With 45 million people in Southeast Asia lacking access to electricity and a large number of islands with insufficient and expensive fossil-based power generation, the need to increase renewable energy implementation is evident. To do so, a replicable way for planning and implementing renewable power systems is crucial to increase the implementation speed and achieve SDG7 in an efficient and least-cost way. We present a geospatial approach for characterising the island landscape of Southeast Asia. First, we apply geospatial administrative and demographic data, as well as renewable resource data to describe the island landscape. Second, we provide a comparison of state-of-the-art energy system modelling software. We conclude with the utilisation of selected energy system modelling software to simulate the cost-optimised renewable energy system for typical island groups based on the predefined island landscape. The findings of our analysis provide a detailed overview about the island landscape of Southeast Asia and the respective potential for renewable-energy-based microgrids to supply the remote islands with affordable, reliable, and sustainable energy as demanded by the SDGs.

Keywords Small islands · Renewable energy · Solar potential · Micro-grids · Energy system modelling · Open source · Levelised cost of electricity

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P. Bertheau (✉) · M. M. Hoffmann · A. Eras-Almeida · P. Blechinger
Reiner Lemoine Institut, Rudower Chaussee 12, 12489 Berlin, Germany
e-mail: paul.bertheau@rl-institut.de

P. Bertheau
Europa-Universität Flensburg, Auf Dem Campus 1, 24943 Flensburg, Germany

A. Eras-Almeida
Instituto de Energía Solar, Universidad Politécnica de Madrid, Av. Complutense 30, 28040 Madrid, Spain

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1 Southeast Asian Island Landscape

Southeast Asia is one of the world's regions with the most islands including the two of the largest archipelagic states, Indonesia and the Philippines [1], as well as other countries with their territories scattered over the sea. This geographic uniqueness brings certain challenges for infrastructure development, especially for providing access to clean energy. This relates to the UN's sustainable development goal (SDG) 7, which is to "ensure access to affordable, reliable, sustainable, and modern energy for all" [2]. In Southeast Asia, this can be best accomplished by renewable energy (RE)-based microgrid or "island" grid, given the availability of renewable resources [3] and the remoteness of many islands, which prevents other supply options like grid connection through submarine power cables [4]. In this chapter, we focus on understanding renewable energy supply options for microgrids on Southeast Asian islands and present different simulation and optimisation tools in order to assess the techno-economic feasibility of such systems.

The term "Southeast Asia" is used interchangeably for a group of ten (usually the ten member states of the Association of Southeast Asian Nations) [3] to twelve Asian countries [5] located between China and Australia, which are all characterised by a tropical climate [6]. For the analysis presented here, we are focusing on the following ten countries: Brunei, Cambodia, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam. Laos, the only landlocked country, is excluded from further analysis. Most of these countries are characterised by dynamic demographic and economic growth [7]. As a consequence, their energy demand rose by 50% from 2000 to 2010 and is projected to triple by 2040 [8]. Simultaneously, the region is affected by the impacts of climate change, including the increasing frequency of extreme weather events [5] and less reliable monsoon patterns [9]. Therefore, the countries are challenged to meet an increasing energy and electricity demand and at the same time mitigate emissions to fulfil their climate protection targets [10]. This demonstrates that a decarbonisation of the energy sector is of high importance and that new generation capacities need to be more sustainable [11].

Currently, more than 45 million people lack access to electricity in Southeast Asia, of whom at least 50% live on small and remote islands [8]. Smaller islands often cannot be connected to the central grid, so if power is available, it is usually supplied by diesel generators [12]. The use of diesel fuel for power generation is one of the most expensive ways to supply electricity due to increasing world market prices and high local transportation costs [13]. In addition, the risk of local pollution by diesel fuel spills, noise, and exhaust gases is high. One solution to reduce the use of diesel fuel is the introduction of RE technologies into these diesel-based supply systems [14]. This results in the hybridisation of fossil-based energy systems, with energy storage systems facilitating high RE shares [15]. Key arguments for hybridisation are reduced diesel fuel consumption, which leads to decreased greenhouse gas (GHG) emissions and often also to reduced power generation costs. For islands without electric power supply, smart and hybrid energy systems comprised of RE, storage technologies, smart IT, and control systems provide a promising solution for electrification [16]. Overall, an implementation of RE strives towards the fulfilment of the SDG7, which can be met by an overall agenda of energy access and climate protection in the region [2].

Despite an existing potential for hybridisation and RE-based microgrids on Southeast Asian islands [15], the current status of RE implementation is rather low. Through our study, we want to support and increase implementation speed by removing barriers to project development and planning. The first barrier is the identification and overview of existing islands, which is currently missing. Here, we apply a geospatial analysis showing the socio-economic characteristics of all islands of Southeast Asia between 100 and 100,000 inhabitants and their solar and wind potential. The second barrier is to find the matching system configuration for hybridisation. This is addressed via three case studies, in which we show first the applicability of different simulation tools and second the techno-economic feasibility of solar-battery-based hybrid systems for island energy supply. The structure of this chapter follows the presented challenges.

1.1 Geospatial Analysis of Island Landscape

In order to characterise and describe the island landscape of Southeast Asia, we conduct a geospatial analysis. Initially, we identified the Global Administrative Areas (GADM) dataset (v. 3.6) as a suitable database of the contour of all land masses in Southeast Asia [17]. We limit the dataset to the ten case study countries and exclude the continental landmasses for Cambodia, Malaysia, Myanmar, Thailand, and Vietnam. Finally, the dataset yields a number of 13,387 islands with a total area of more than 2.4 million km^2. The disparity to other stated islands' quantities in literature, for example >17,500 islands for Indonesia [18] and >7400 for the Philippines [19], is due to simplifications of the GADM dataset. However, the GADM dataset provides land areas similar to official statistics [20], e.g. for Indonesia $+$ 4.2%, Philippines $-$0.8%, Singapore $-$1.8%, and Timor-Leste $+$0.3%. To validate this data, we compare the applied GADM dataset for the example of the Philippines to a more detailed dataset provided by the Philippine National Mapping and Resource Information Authority (NAMRIA). We observe that the simplification of GADM merges smaller single islets and entirely misses some very small islands. This is illustrated for an example in Fig. 1, where the GADM dataset in red and the NAMRIA dataset in yellow. In conclusion, we found the GADM dataset sufficient for our analysis. It is the only dataset available for the entire Southeast Asian region, covers most of the island areas and only shows data gaps for very small and potentially uninhabited islands.

After identifying the location and size of each island, we calculate population statistics for each island based on the WorldPop datasets [21, 22] (applying the 2015 estimation) by using geospatial raster statistics algorithms. Based on the approach, we identify a population of more than 385 million distributed over the island landscape as

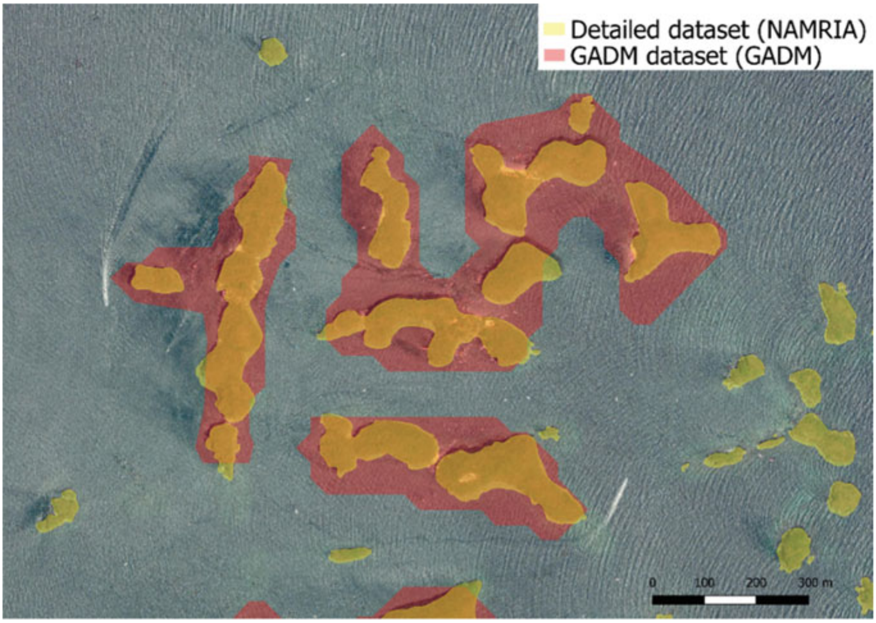

Fig. 1 Comparison of the applied island dataset (GADM) to a detailed island dataset for the Philippines (NAMRIA)

presented in Table 1. The analysis highlights that the major share of 70% of individual islands hosts only a minor share of the population. At the same time, the seven most populated islands comprise more than 82% of the population of all islands.

For our further analysis, we conclude that the first two groups of more than 11,400 islands hold no potential for microgrid deployment, since they are mainly uninhabited or only few people are living there (estimated maximum of 100). This

Table 1 Number of islands per population class and the respective total island population. Further analyses focus on population classes in the bold rows

Population class	Islands	% of islands	Total population	% of population
<10	9379	70.1	8517	0.002
<100	2037	15.2	75,592	0.02
<1000	**1224**	**9.1**	**420,701**	**0.1**
<10,000	**502**	**3.7**	**1,622,835**	**0.4**
<100,000	**181**	**1.4**	**5,868,787**	**1.5**
<1000,000	41	0.3	13,704,189	3.6
<10,000,000	17	0.1	47,361,254	12.3
>10,000,000	7	0.1	316,405,519	82.1
Total	13,388	100	385,467,394	100

means the electricity demands are small and the required effort for delivering the components and construction material of microgrids including distribution grids on site is very high. Instead, such islands could be provided with solar home systems[1] as an initial step to allow for basic electricity supply of households and small commercial customers [23]. Additionally, we apply an upper threshold and exclude islands with more than 100,000 inhabitants. Even though some islands with a population larger 100,000 are currently powered through microgrids, such islands are more likely to form major central electricity systems in the future. These systems require large base load and peak load capacities as well as reserve capacities and are more likely to be interconnected with submarine cables or form individual larger conventional power grids. In conclusion, we focus on islands with a population of 100–100,000 inhabitants, comp. [15]. This selection results in 1907 islands with a population of 7.9 million, which creates an interesting market for microgrids in Southeast Asia. Figure 2 provides an overview map of the considered islands.

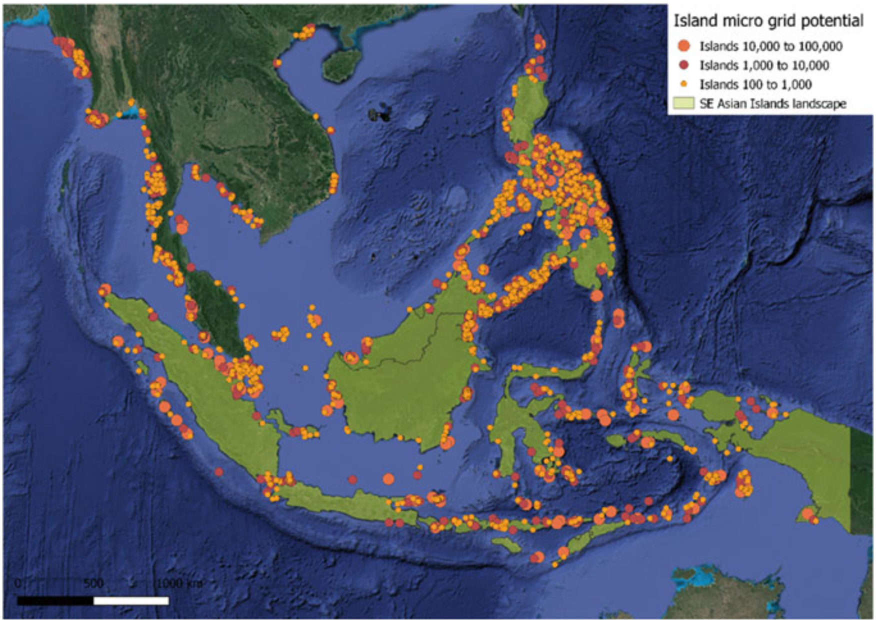

Fig. 2 Overview map of identified islands with microgrid potential

[1] More detailed discussion on SHS and its applications are explored in Chapter "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?" of this book.

1.2 Classification of Island Landscape and Implications for Microgrids

For the classification of the island landscape, we consider key socio-economic data for each island, specifically population, gross domestic product (GDP), physiographic data (area), accessibility data (remoteness), and renewable resource data (global horizontal irradiance (GHI) and wind speed). Geospatial raster statistics are applied to summarise population and GDP per island and to derive mean values for remoteness, GHI, and wind speed. The area per island is calculated applying the field calculator function in the utilised geospatial information software. The applied datasets are listed and described in Table 2.

For each of the three considered island population size classes, we highlight the characteristics per country. Countries with less than twenty islands are reflected in a summary group named "other".

For the least populated islands with a population between 100 and 1000 inhabitants (Table 3), we find a typical mean island population of around 350 for all considered countries. Most of these islands are located in the Philippines (501 islands) and Indonesia (435) with a total population of 420 thousand. Average GDP per capita for the smaller islands is mostly below the countries' average values, whereas mean island sizes are small in the Philippines, Malaysia, and Vietnam (<10 km^2), larger sizes are found in Thailand, Myanmar, and Indonesia (>10 km^2). The solar energy

Table 2 Applied datasets for classification of the island landscape

Parameter	Description	Unit	Source
Population	The applied dataset provides the number of inhabitants on a raster scale. Pixel resolution is approximately 100 m. The population is summarised per island.	#	[22, 21]
Area	Island size is calculated in square kilometres.	km^2	GIS calc.
GDP per capita	The dataset provides the spatially disaggregated gross domestic product (GDP). Information in million USD is provided in pixel resolution of approx. 1 km. For each island, the GDP is summarised and divided by the population to obtain GDP per capita	USD/capita	[24]
Remoteness	The applied dataset provides accessibility in minutes from the nearest city with more than 50,000 inhabitants on a raster scale. Pixel resolution is approx. 1 km	minutes	[25]
GHI	The dataset provides global horizontal irradiance (GHI) in kWh per m^2. Information is provided on a pixel scale of approx. 1 km	kWh/m^2/y	[26]
Wind speed	The dataset provides average wind speed in metre per second in 80 m hub height. Information is provided on a pixel scale of approx. 1 km	m/s	[27]

Table 3 Overview on islands with 100–1000 inhabitants per country

Country		Islands	Total Pop.	Island Pop.	GDP/capita	Area	Remoteness	Solar potential	Wind potential
		#	#	mean capita	mean USD/capita	mean km^2	minutes	mean $kWh/m^2/y$	mean m/s
Philippines	Value	501	164,446	328	424	1.7	234	1830	4.9
	Std. Dev.			221	2508	2.3	101	66	1.4
Indonesia	Value	435	157,890	363	1414	17.6	364	1788	3.5
	Std. Dev.			246	4011	26.4	306	157	0.8
Myanmar	Value	107	34,640	324	336	11.0	272	1820	3.8
	Std. Dev.			240	2669	21.9	150	22	0.6
Malaysia	Value	92	32,940	358	2114	2.9	223	1804	3.3
	Std. Dev.			223	8582	3.1	135	60	0.7
Vietnam	Value	37	12,678	343	2088	5.7	174	1567	5.9
	Std. Dev.			226	3896	6.1	69	262	0.8
Thailand	Value	35	12,631	361	6789	10.9	196	1836	3.9
	Std. Dev.			214	10,265	19.6	109	34	0.6
Other	Value	17	5475	287	11,427	9.1	330	1828	3.6

potential is very good for all islands with most values in the range of 1800 kWh/m^2/y. The mean solar potential for Vietnamese islands is lower than the average, but their wind power potential is the highest with 5.9 m/s wind speed.

For islands with a population between 1000 and 10,000 inhabitants (Table 4), we find an overall population of 1.6 million. Typical islands of this group have a mean population of approximately 3000–4000 island inhabitants, with a larger spread for Indonesian islands compared to other countries. The solar potential is similarly high for the island group (mean of 1800 kWh/m^2/y), the wind power potential is the highest in the Philippines with mean of 4.9 m/s.

Islands with a population between 10,000 and 100,000 inhabitants (Table 5) comprise the largest total population with 5.8 million. Of those, more than 4.7 million are living on Philippine and Indonesian islands. These larger islands hold a typical average population of 35,000. The Indonesian islands are more diverse in terms of economic activity and island area, compared to the uniform group of Philippine islands. The group of islands comprised as “other” islands are mainly comprised of larger islands in Myanmar (19) and Malaysia (15).

1.3 Implications for Future Microgrid Development

The classification reveals that there exist many islands in Southeast Asia, which are suitable for microgrid deployment in terms of their population size and renewable resource potential, especially for solar power. Most of the islands with a population lower than 1000 are likely not provided with electricity yet. As shown earlier, such islands are mostly very remote with low purchasing power (see Table 3), indicating that initial electricity demands will be low. Microgrid system designs need to address these preconditions. Based on the fact that most islands worldwide rely on diesel power systems to supply the electricity demand [28], we assume that the identified islands with a population of more than 10,000 are already supplied with such diesel generators. Here, the implementation of RE serves for the hybridisation of former fossil-fuelled island grids. The use of electricity for productive use facilitates the integration of RE, as the productive demand typically peaks in parallel with the highest daily solar yields. A stepwise implementation, e.g. to form a solar-diesel grid (RE share of 20–30%) and a later implementation of battery storage (RE share 40–100%) can facilitate the mitigation of diesel fuel combustion and minimise initial investment costs. In the group of islands between 1000 and 10,000 inhabitants, both cases, meaning no power supply yet and diesel-based power generation are likely to be found. Therefore, both implementing greenfield RE-based hybrid systems and stepwise implementation of RE capacities into diesel grids can be approaches for sustainable power supply and energy access.

Future microgrid planning efforts should focus on both providing electricity access as a large number of projects can be realised and on hybridisation as more beneficiaries may be reached. The Philippines and Indonesia clearly hold the largest potential for microgrids, so it is important to understand the market and regulatory framework

Table 4 Overview on islands with 1000 to 10,000 inhabitants per country

Country		Islands	Total Pop.	Island Pop.	GDP/capita	Area	Remoteness	Solar potential	Wind potential
		#	#	mean capita	mean USD/capita	mean km^2	minutes	mean $kWh/m^2/y$	mean m/s
Philippines	Value	191	589,396	3086	773	15.4	221	1848	4.6
	Std. Dev.			2299	662	24.2	104	73	1.5
Indonesia	Value	183	579,899	3169	2231	95.0	358	1801	3.4
	Std. Dev.			19,102	5179	284.6	198	1	0.0
Myanmar	Value	56	177,062	3162	220	48.6	323	1821	3.4
	Std. Dev.			2123	236	69.8	171	24	0.5
Malaysia	Value	39	170,792	4379	4355	36.1	251	1800	2.9
	Std. Dev.			2597	7748	50.8	156	70	0.6
Other	Value	33	105,686	4040	48,900	285.1	301	1697	3.5

Table 5 Overview on islands with 10,000–100,000 inhabitants per country

Country		Islands	Total Pop.	Island Pop.	GDP/capita	Area	Remoteness	Solar potential	Wind potential
		#	#	mean capita	mean USD/capita	mean km^2	minutes	mean $kWh/m^2/y$	mean m/s
Indonesia	Value	77	2,674,521	34,734	2142	972.6	334	1761	3.3
	Std. Dev.			24,680	3422	1,533.2	290	140	0.7
Philippines	Value	61	2,036,667	33,388	831	135.9	253	1826	4.4
	Std. Dev.			26,536	1409	173.6	120	73	1.3
Other	Value	43	1,157,599	39,589	12,834	202.5	336	1792	3.8

that could cause potential bottlenecks for implementation in these two countries followed by Malaysia, Myanmar, Thailand, and Vietnam. Additionally, the deployment of microgrids needs to account for the rising impact and risk of climate change effects in Southeast Asia. This includes droughts, floods, extreme weather events, and sea-level rise [10]. Therefore, microgrid designs should incorporate flexibility and resilience to the above-mentioned threats.

2 Application of Energy System Modelling Tools

The GIS analysis results in a pre-selection of islands in Southeast Asia, which are potential microgrid project sites. To determine the actual feasibility of a microgrid at these project locations, a more detailed analysis of the islands has to be performed. This means the load demand needs to be understood so that potential supply options can be suggested. There is a large variety of software tools to determine pre-feasibility of microgrid projects as well as to simulate and optimise energy power systems and sizes of components [29]. These tools optimise the sizes of components of energy systems and use dispatch strategies to supply the demand for the specific case study. In order to identify possible renewable energy investments, we apply different software tools to simulate hybrid microgrids for a selection of three case studies. The results are useful for planners and decision makers to understand typical solutions for RE microgrids and to find the most suitable tool for their use case.

The simulation tools selected have been developed or used by the authors and are comprised of: the simplified planning tool for hybrid systems (SPT), developed by researchers of the Reiner Lemoine Institute (RLI) initially for the Philippine context, which is implemented in Microsoft Excel. The Python 3-tool Offgridders—available open source—and the proprietary software Hybrid Optimization of Multiple Energy Resources (HOMER). They are applied to three exemplary Southeast Asian islands, distinguishable by population and economic activity and representing small, mid-size, and large islands (in terms of population). The simulation results of the tools for each case study island are presented comparatively.

2.1 Literature Survey on Simulation Tools

The three energy system modelling tools applied are only a selection of a diverse group of existing energy system modelling tools that have been developed for many purposes. Scientific literature provides several review studies to describe and categorise such tools: Ringkjøb et al. reviewed 75 modelling tools for analysing and planning energy and electricity systems [30]. Sinha and Chandel explicitly focused on tools for hybrid renewable energy systems and reviewed 19 software tools [29]. Connolly et al. highlighted 68 computer tools for analysing the integration of RE in energy systems and analysed 37 of those in more detail [31]. Anoune et al. compared

11 different sizing tools for PV wind-based hybrid renewable energy systems [32]. Sharma et al. compared the environmental assessment methodology in five hybrid system simulation software tools [33].

HOMER is considered for review in all of the above-mentioned studies and applied in many case studies, e.g. [34–39], highlighting its widespread use. It is therefore applied in our case studies and can serve as a reference tool. As it is a relatively new tool, Offgridders has only been used once for scientific papers [40]. Building up on the open source python-library Open Energy Modelling Framework (oemof) [41], the core optimisation methodology of Offgridders has been scientifically validated through the oemof developer and open modelling community. Other software tools mentioned for the application of hybrid and microgrid modelling with significant users are RETScreen [29, 31], H_2RES [30], INSEL [29], iHOGA [33], and TRNSYS [30, 33]. A particular challenge mentioned is that most proprietary software does not allow for customisation of its internal computation method and are therefore a "black box" for users [29]. Additionally, license fees limit the applicability of such tools [42]. Both contradict the scientific criteria of replicability, accessibility, and reproducibility of research results and approaches [41]. Open source software tools comply with the above-stated criteria and are increasingly considered as sufficiently reliable for policy advice [43]. As the group of developers is diverse, tools are developed based on many different motivations and their functions differ widely [43]. However, open source software tools require a large and active community of developers and users to incorporate and update necessary functions [42]. Otherwise, such tools tend to become outdated quickly and limited software support discourages application [29].

For future improvements of tools, the scientific community recognises the necessity to improve energy system modelling tools, including sustainability criteria. Such critique includes the capability of the tools to inform users about the environmental impact of the suggested system designs [33]. Most tools consider emissions—if at all—solely during the operational phase as a proxy of the combusted diesel fuel. Here, the inclusion of life cycle assessment approaches could add information for developing sustainable energy systems [33]. Most microgrid tools neglect the grid impact and network constraints [43], whereas the integration of intermittent RE sources can pose a larger challenge in island grids than larger grid networks [44, 45]. Other concerns address the user-friendliness, incorporation of emerging energy technologies, and more flexible control techniques [29].

2.2 Description of Tools Applied

Microgrid design and simulation tools can make use of multiple methods and levels of detail to determine both microgrid architecture and performance. This, in turn, can lead to significantly differing design and feasibility results of single project locations. It is therefore essential to choose a simulation tool according to the needs of the study at hand and be aware of the effects and uncertainties introduced by this choice. According to Moretti [46], tools can be divided into three main classes: an *analytical* *model* simplifies the simulation of the microgrid for a limited time period and makes use of aggregated factors to determine the system architecture. The influence of dispatch on system design is not addressed, and as such, both resulting economic and technological feasibility remain an estimate.

Two-layer models add a level of detail by addressing design as well as dispatch. Still, these two layers are optimised separately, determining first an architecture and then, according to a previously defined set of dispatch rules, evaluating system performance. Hence, the optimal system design is determined by iteration. Simulation tools integrating the optimisation of design and dispatch can be labelled *single-layer models*. The optimisation of this intertwined problem requires powerful tools, for example mixed integer linear programming.

Analogously, in order to show the applicability of and compare different simulation tools, we selected three different tools for a comparative evaluation of the case studies. The SPT is a simplified excel-based tool, which targets project planners and decision makers for pre-feasibility analyses and can be categorised as an analytical model. HOMER targets commercial developers of hybrid projects and is a typical two-layer tool [33]. Offgridders is an open source tool [47, 48], which targets the scientific community of researchers and tool developers and is representative for the single-layer type. It makes use of oemof [41] to generate a model of an electricity supply system to be designed, and to solve the resulting set of linear equations. All tools follow the same principle of inputs, processing (simulation/optimisation), and output as shown in Fig. 3.

The tools can be distinguished along those steps and by other categories. Table 6 gives an overview of the specifics of the three applied tools. It provides detailed information about input and output data, processing, flexibility, accessibility, and developers. The main input data that these tools require are load, resources information, component costs, and project features. In a simulation scenarios (dispatch simulation), the energy flows are simulated along predefined dispatch strategies (SPT, HOMER) or are simulated including the optimisation of dispatch strategies (Offgridders). Meanwhile, in the optimisation scenarios (dimensioning of system components

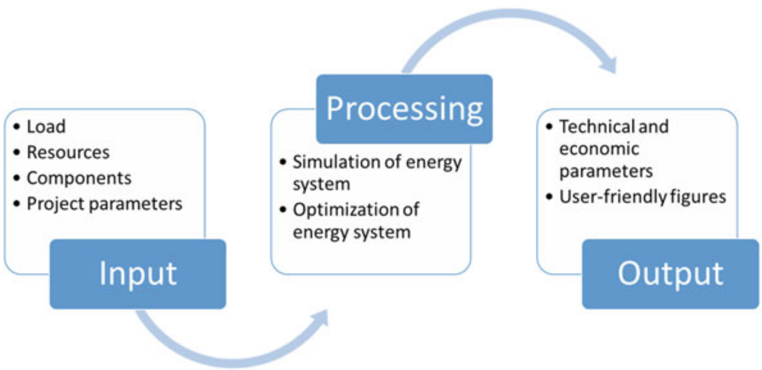

Fig. 3 Conceptual flow of energy system simulation tools

Table 6 Comparison of applied tools

Category	Detail	SPT 3.0	HOMER 3.13.1[a]	Offgridders
Input	Load	Electricity demand per hour for one reference day	Hourly data (handling capacity) for one year	Hourly demand profile for a reference period, i.e. a variable number of days, ideally a year
	Resources	Based on average values	Data with time steps of different sizes from 60 min to one minute. Solar and wind data can be downloaded from national renewable energy lab or NASA sources. These resources and others such as fuel, hydro and biomass resources can be imported or manually introduced by the user	Hourly time series for potential solar or wind plant electricity output for the reference period
	Components	PV, wind, hydro, battery, diesel	PV, wind, hydro, battery, converter (inverter/rectifier), generator (diesel, natural gas, methanol, and others), controller, boiler, electrolyser, hydrogen tank, grid, thermal load controller	PV, wind, battery, converters (inverter/rectifier), transformer station connecting to the national grid (in/out), diesel
Processing	Simulation	Calculation of dispatch for one reference week in hourly increments	Calculation of dispatch for one reference year in hourly increments (can be adjusted to minutes)	Parallel optimisation of capacity and dispatch of system assets Cost-optimal dispatch, not rule-based

(continued)

Table 6 (continued)

Category	Detail	SPT 3.0	HOMER 3.13.1[a]	Offgridders
	Optimisation	No dispatch/system optimisation	Dispatch strategy to control the operation of generators and storage banks to supply the demand. Two dispatch strategies can be used: load following and cycle charging suitable for systems with high and low renewable power, respectively	
	Optimisation algorithm	Scenario analysis to compare configurations	Design process to identify the least-cost option between different scenarios or optimisation using the "HOMER Optimizer"	Solving of a set of linear equations describing the whole system
Output	Technical and economic parameters	Key parameters for selected years (LCOE, CAPEX, OPEX) No detailed energy flows	Detailed parameters (cost and technical) for each component and the project, renewable energy share, emissions. Detailed energy flows	Detailed cost parameters for each component and the project, asset sizing and technical and economic system performance (NPV, LCOE, reliability, renewable share and other)
	Visualisation	Simple figures	Detailed and customised figures	Figures of the system's electricity flows
Flexibility		Fixed tool	"Black box" code used, but control strategies can be implemented via MATLAB Link module	Flexible tool, open-source, adaptable electricity system configurations, other components or energy vectors can be added

(continued)

Table 6 (continued)

Category	Detail	SPT 3.0	HOMER 3.13.1[a]	Offgridders
Additional features		–	Additional modules to design or improve dispatch strategies: generator order, combined dispatch, homer predictive. Multi-year and sensitivity analyses are also possible	Central grid connection can be subject to blackouts, blackout randomisation, batch-analysis of a number of project locations, automated sensitivity analysis
Developer		Reiner Lemoine Institut	National Renewable Energy Laboratory	Hoffmann, Reiner Lemoine Institut
Accessible via		https://reiner-lemoine-institut.de/en/	https://www.homerenergy.com/ (For testing: the software is available for 25 days)	https://github.com/smartie2076/Offgridders

[a] www.homerenergy.com (accessed: July, 31 2019) HOMER Pro. Version 3.13.1

and dispatch simulation) system designs are identified based on least-cost energy supply (Offgridders, HOMER). The open source tool Offgridders provides the flexibility to perform code modifications, adjusting to the specific conditions of the performed case study. Finally, the output data, which can be used to make comparative analyses, are Levelised Cost of Electricity (LCOE), RE share, and fuel consumption among others. Depending on the chosen simulation tool, the extent of output information varies.

2.3 Description of Case Study

We apply the three outlined energy system modelling tools for each of the pre-identified island classes. The application serves to better understand the techno-economic potential for hybrid microgrids on these islands and to compare the usability of the different tools. The three case study islands are chosen from real project sites for which data are available. The selection is conducted to be representative for small, mid-size, and large Southeast Asian islands.

- Small island: Islands with 100–1000 inhabitants

This case study island represents the most numerous island group characterised by low populated islands with few productive loads. Many of the considered islands are not yet electrified. The selected case study island has a population similar to the average of 350. The electricity demand is characterised by a high evening peak and low average demand (Fig. 4). The peak load is 12.6 kW, and the average solar potential is 1807 kWh/m^2/y. The island is served by one diesel generator with a size of twice the peak load. Such oversizing can be commonly observed in small island grids serving one or few villages.

- Mid-sized island: Islands with 1000–10,000 inhabitants

This case study island has a population of around 3000, which is in the typical size range for islands of this class. The load profile is as well characterised by an evening peak load but with a higher average load (Fig. 4). Peak load is 138 kW, and the average solar potential is 1802 kWh/m^2/y. Two diesel generators each with a capacity equal to the peak load provide power supply on the island. By implementing two generators, the security of supply is increased as one diesel unit can supply all of the demand while the other one is under maintenance.

- Large island: Islands with 10,000–100,000 inhabitants

We select a case study representing a population of approximately 40,000 with a peak load of 1.8 MW. In contrast to the two former island groups, this island has a midday peak due to productive and economic activities during the day (Fig. 4). The solar potential is 1840 kWh/m^2/y. Three diesel generators are implemented with a capacity of 1.2 MW each.

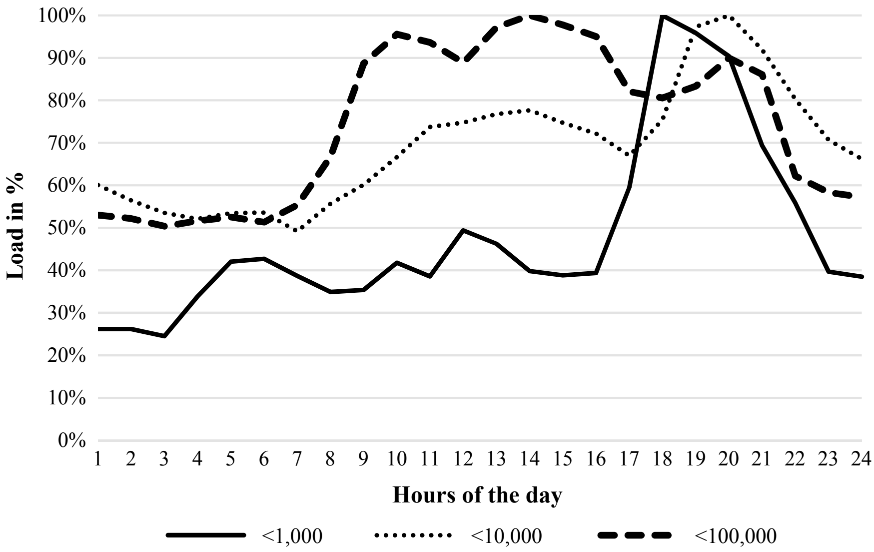

Fig. 4 Applied load profiles for the three applied case studies

As wind power potential is largely dependent on local island conditions and relatively low along the tropics, it cannot be easily generalised and will not be considered in the energy systems of our exemplary case studies. Since we identified a high potential for solar PV for the entire island landscape, we consider solar-battery-diesel hybrid microgrids for the modelling of energy systems. Given the objective of comparing the energy system modelling tools described, we insert the input parameters in the most similar way possible. However, due to different input schemes of the individual tools this is not possible for some of the parameters. An example is the solar generation per hour, which is inserted as an annual profile for Offgridders and HOMER and as a weekly profile in SPT. The same holds true for the electricity demand profile. Another difference is that no minimal loading and fixed efficiency for the diesel generator is applied in Offgridders, in contrast to a minimal loading of 30% and variable efficiency depending on the loading of the diesel generator in HOMER and SPT. Table 7 provides the applied economic and technical parameters.

We apply researched projected cost and technical assumptions for describing the specific components of the microgrid in terms of initial costs, operational expenditures, lifetime and further specified technical parameters. For solar PV plants, we apply initial investment costs of 1000 USD/kWp, 2% OPEX and lifetime of 20 years [49]. We consider lithium-ion battery technology as energy storage system, considering it as the most suitable energy storage technology on islands, given the expected cost reduction, high efficiency, and longer life cycles compared to other technologies [50, 51]. CAPEX are 500 USD per kWh installed capacity, OPEX are 5 USD/kWh per year, and the assumed lifetime is 10 years; other technical parameters are round-trip

Table 7 Economic input parameters for case study analysis

	Parameter	Unit	Value
PV	CAPEX	USD/kWp	1000
	OPEX	USD/kWp/y	20
	Lifetime	y	20
	Solar output	kW/kWp/h	Year (Offgridders, HOMER) Week (SPT)
Battery	CAPEX	USD/kWh	500
	OPEX	USD/kWh/y	5
	Lifetime	y	10
	C-rate	kW/kWh	1
	Max. depth of discharge	%	80
	Charging efficiency	%	90
	Discharging efficiency	%	90
Diesel	Installed capacity	kW	2 times peak demand
	CAPEX	USD/kW	500
	OPEX (fix)	USD/kW/y	6
	OPEX (var)	USD/kWh	0.03 (SPT, Offgridders) var. (HOMER)
	Lifetime	Y	10
	Minimal loading	% of max power	0 (Offgridders) 30 (SPT, HOMER)
	Fuel use per kWh	l/kWh(el)	0.33
	Generation efficiency	%	30.9 (Offgridders) var. (SPT, HOMER)
Other	Fuel price	USD/l	0.8
	Project lifetime	Y	20
	WACC	%	10
	System stability criteria	%	30
	Demand	kW, hourly	Year (Offgridders, HOMER) Week (SPT)

efficiency of 81% and a maximum depth of discharge of 80% [52, 53]. For designing the diesel generator system, we assume a fixed capacity twice the peak load for each case study [54]. We apply CAPEX of 500 USD/kW, fixed operational costs of 6 USD/kW/y and variable operational costs of 0.03 USD/kWh in Offgridders as well as SPT [13]. For HOMER, we apply default values of 0.25 USD per operating hour for diesel generators <100 kW, 2 USD per operating hour for diesel generators <1000 kW, 10 USD per operating hour for generators >1000 kW. A stability criterion is applied which ensures that 30% of the hourly load can be supplied by using the generator or by having sufficient battery capacity and power as backup. We set diesel costs at 0.8 USD/l, reflecting procurement costs plus additional transport costs [13]. Project lifetime is set to 20 years with an interest rate of 10%.

2.4 Case Study I: Small Island

At first, we present a diesel-only and hybrid scenario for the small case study island. Evaluating the likely current electricity supply system of the smallest island, a sole diesel microgrid with only one single generator of 25 kW capacity, the simulation tools result in a wide range of LCOE: The electricity supply costs vary from 34 USDct/kWh (Offgridders), 59 USDct/kWh (HOMER) to up to 60 USDct/kWh (SPT). A closer look into the cost components reveals that these differences spring both from differing fuel consumption and from annual operational costs of the generator (Table 8). This highlights the differences of the simulation tools with regard to their diesel generator models: while Offgridders assumes constant efficiency and no minimal loading, both SPT and HOMER take into account the dependency of the generation efficiency on the diesel generator's load factor and a minimal loading, resulting in twice as high fuel consumption. The generator constantly operates in part load, which leads to very low efficiencies in the SPT and HOMER simulations. Excess generation in times of low demand, resulting from the generator's minimal loading, increases the fuel consumption additionally.

When designing a hybrid microgrid for the smallest island, all three tools result in an optimal renewable share of about 30%. However, the capacities to reach this percentage vary: while the SPT suggests an installation of 20 kWp PV combined with 8 kWh lithium-ion battery, Offgridders reaches the renewable penetration with only 14 kWp PV and 2.6 kWh battery. In contrast to this, HOMER recommends an installation of 20 kWp PV and a larger battery capacity of 28 kWh. In case of Offgridders, the low installed capacities are caused by its methodology: with perfect foresight and constantly high diesel efficiency, low PV, and battery capacities pose the least-cost option. HOMER is able to use the battery capacities to decrease diesel operational hours, and as such, the diesel generator's operational costs.

The investment into hybridisation (SPT: 24,000 USD, Offgridders: 15,300 USD, HOMER: 34,000 USD) allows to decrease the island's system's estimated fuel consumption by a large margin—by half in the case of SPT and HOMER. This saves 4,000–16,000 USD/a in fuel expenditures, leading to lower LCOE. The SPT shows

Table 8 Results of energy system modelling tools for the three case studies

	System type	Tool	LCOE	Diesel units	Fuel consumption	Fuel cost	Annual O&M costs diesel
			[USD/kWh]	[#]	[thousand litre/a]	[kUSD/a]	[kUSD/a]
Small island	Diesel	SPT	0.60	1	34.2	27.4	2.3
		Offgridders	0.34	1	17.5	14.0	1.7
		HOMER	0.59	1	33.8	27.1	2.2
	Hybrid	SPT	0.39	1	17.6	14.1	1.3
		Offgridders	0.29	1	12.4	10.0	1.3
		HOMER	0.35	1	14.2	11.3	0.7
Mid-sized island	Diesel	SPT	0.34	2	298	238	26.7
		Offgridders	0.32	1	276	221	26.7
		HOMER	0.36	2	326	260	24.8
	Hybrid	SPT	0.29	2	201	161	18.2
		Offgridders	0.27	1	183	146	18.3
		HOMER	0.28	2	192	154	9.4
Large island	Diesel	SPT	0.32	3	3921	3136	374.4
		Offgridders	0.32	1	3881	3105	374.4
		HOMER	0.34	3	4191	3353	350.4
	Hybrid	SPT	0.26	3	2344	1875	226.5
		Offgridders	0.26	1	2283	1826	229.1
		HOMER	0.26	3	2071	1657	121.4

electricity costs of 39 USDct/kWh, Offgridders of 29 USDct/kWh and HOMER of 35 USDct/kWh.

2.5 Case Study II: Mid-Sized Island

For the second case study, similarly, we simulate a diesel-only and a hybrid system. Powering a mid-sized island with a diesel-based microgrid is cheaper than powering a small island, with LCOE ranging from 32 USDct/kWh (Offgridders) to 36 USDct/kWh (HOMER) (Table 8). Splitting the diesel generator capacity in two units allows for a more appropriate supply of the hourly load. Annual fuel consumption also varies to a lower degree. It is important to underline that this is achieved through two generators of 138 kW being installed in case of SPT and HOMER, as it is often the case in microgrids with increasingly high peak demand. As such, the average generation efficiency is increased dramatically—as one of the generators can even operate on full load during peak demand times.

The costs of electricity supply for the mid-sized island can further be decreased if a hybrid microgrid is installed, with LCOE of 27 USDct/kWh (Offgridders), 28 USDct/kWh (HOMER), and 29 USDct/kWh (SPT). This is achieved with an increased renewable share between 32 and 39% (Fig. 5). The PV capacity installed exceeds the peak demand in all three cases and is almost twice the peak demand (Fig. 7). Overall, the SPT estimates that 276 kWp PV and 57 kWh battery should be installed, Offgridders recommends 267 kWp PV and 44 kWh battery, and HOMER results in 266 kWp PV and 180 kWh battery capacity. Such an installation sums to capital costs of 305,000, 289,000, and 356,000 USD, respectively, compared to diesel generator capital costs of 138,000 USD. This decreases fuel consumption and fuel costs by about a third in all simulation tools. HOMER, again, uses the large battery capacity to decrease the operation hours of the diesel generator (Fig. 6). We assume

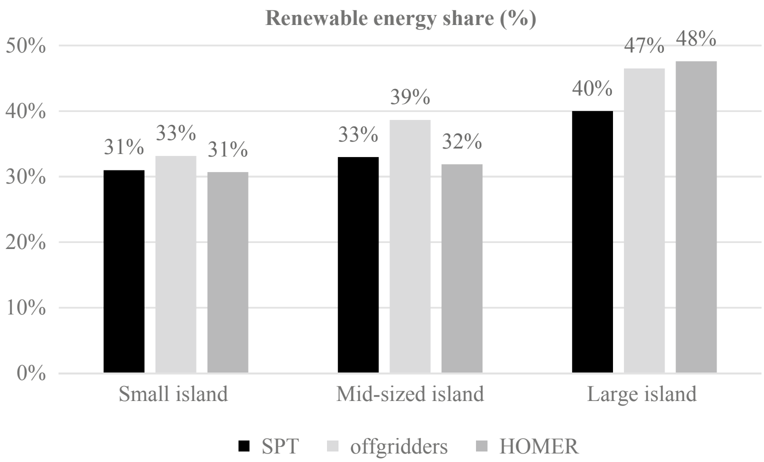

Fig. 5 Renewable energy share for the three applied case studies

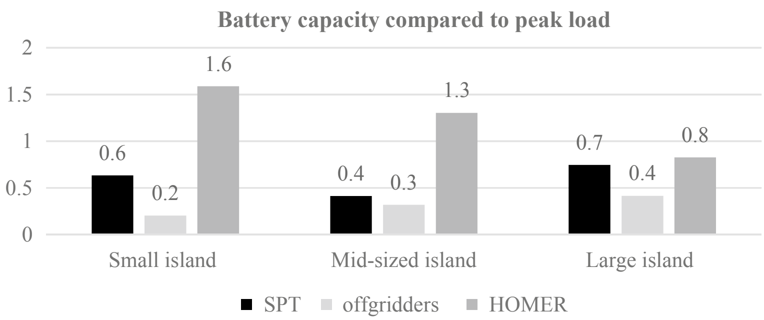

Fig. 6 Battery capacity compared to peak load for the three applied case studies

this is based on the detailed modelling of diesel and battery dispatch and optimising the battery lifetime through cycle charging. This results in higher required battery capacities.

2.6 Case Study III: Large Island

For the final case study, a diesel and a hybrid system configuration is simulated analogously to the case studies described earlier. Microgrids on large islands often consist of multiple generators. As such, in SPT and HOMER, we assume three generators with a peak power of 1.2 MW each to be already installed on the island. This also allows increasing the times a specific generator runs on a high load factor and may decrease excess generation by running generators on low load factors when demand barely exceeds multiples of 1.2 MW. The fuel consumption estimated by SPT and Offgridders is therefore comparable, while HOMER has the highest fuel consumption due to the most detailed simulation of the individual diesel gensets (Table 8). Supplying the island with electricity through a diesel-powered microgrid is therefore possible at an LCOE of 32 USDct/kWh (SPT, Offgridders) to 34 USDct/kWh (HOMER).

Still, hybridisation of the microgrid enables to decrease the electricity costs further to 26 USDct/kWh (SPT, Offgridders, HOMER). This is possible by replacing 40–48% of fossil-fuelled electricity with renewable generation. SPT and Offgridders estimate a PV capacity of 230–250% of the peak demand (Fig. 7). As such, the SPT would recommend installing 4.1 MWp PV and 1.3 MWh battery at costs of 4.8 million USD, while Offgridders suggests the installation of 4.5 MWp PV and 750 kWh battery investing 4.9 million USD. HOMER's simulation results recommend the

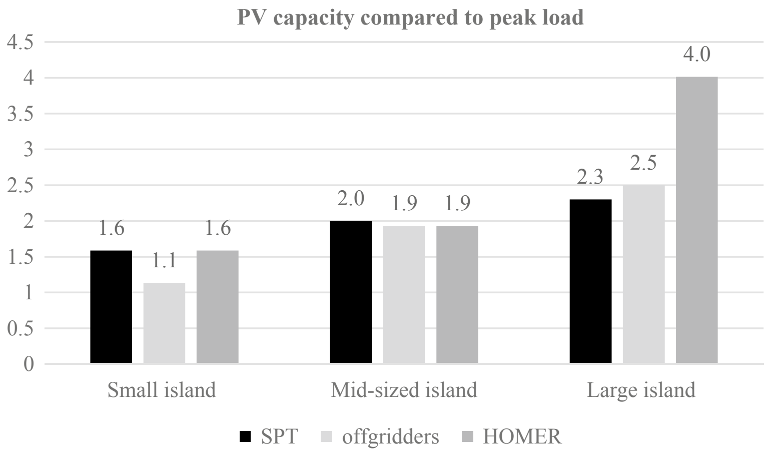

Fig. 7 PV capacity compared to peak load for the three applied case studies

installation of a PV capacity four times the peak demand (7.2 MWp) and 1.5 MWh battery capacity, with capital costs of almost 8 million USD. This large capacity decreases operational hours of the diesel generator almost by half (compared to SPT and Offgridders) and thereby decreases diesel generator operational costs. Judging from the comparably low fuel consumption decrease, these savings are achieved by replacing diesel generator utilisation not only during the day, but also at times at low demand in the evenings or mornings through batteries charged using PV generation.

2.7 Comparative Discussion

The presented case study analysis of the simulated islands shows that microgrid hybridisation is favourable for small, mid-sized, and large islands. While these prospects can be, as a simplification, linked to an islands' population, the actual driver can be found in the demand profile's shape. High evening peaks, common on islands with lower population, disadvantage high PV penetration as the batteries required to supply evening demands are not always economically competitive to fossil-fuelled power generation. With increasing population and business activity, the demand peaks move towards noon, while at the same time, the daily average demand increases and the demand profile flattens. This leads to cheaper systems, in which diesel generators run on higher efficiencies, and PV can be used not only to supply daytime demand, but also to decrease diesel operational time. The second driver to lower LCOE of diesel and hybrid systems is the flexibility of the diesel generators operation and dispatch. Instead of using one generator (first case study), we use two and three generators (cases II and III) to show the effect of increased flexibility and reduced overall minimum load of the power plant.

Especially HOMER showed that microgrid hybridisation could not only replace daytime diesel operation, but also decrease diesel operational hours and increase its efficiency, thus decreasing system costs. Attention has to be paid to the assumed diesel fuel price. Here, a conservative estimation without accounting for future fuel price growth was used, displaying the competitiveness of PV and batteries today but underestimating their benefits in the future.

As presented, the simulation tools displayed similar tendencies but also differing simulation results. While the general tendency of decreasing LCOE and increasing renewable share with increasing population remains true for each tool individually, the actual values can differ largely, especially with regard to optimal capacities and fuel usage. This originates from the different component models and possible settings of each simulation tool, which the user should take into account.

The simulation tools, therefore, have different areas of application. The SPT is able to perform a pre-feasibility study of individual locations with a low need for inputs and a clear interface for the results, which makes it accessible to non-experts. Offgridders has a very low computation time, but relies on simplifications for system assessment. With its ability to evaluate a great number of locations and perform sensitivity analyses, it can identify tendencies and highlight project sites with high potential for future detailed analysis. With its adaptability, it can be used in research. Using HOMER, on the contrary, requires expert knowledge and a long computing time but is able to provide a detailed and implementable system design for a specific project location.

2.8 Advantages and Disadvantages of Applied Tools

The literature review has shown that HOMER can be seen as the current state-of-the-art simulation tool for microgrids. With the SPT and Offgridders, we suggest two alternatives, which are free of charge and can be further developed and adapted by the users. In the following table, the advantages and disadvantages of each applied tool are summarised from the users' perspective.

As stated in Table 9, each tool has certain advantages and disadvantages for different user groups. They can be summarised as follows:

Table 9 Simulation tool comparison from a user's perspective

Tool	Advantages	Disadvantages
Offgridders	• Open source tool which allows for changes in the programming code by the users • Highly flexible tool; any components and dispatch strategy can be added • Allows automated simulation of many islands/scenarios which is beneficial for pre-feasibility studies • Linear optimisation of components' sizes and dispatch allow an outlook on optimal hybrid system's performance	• Limited reference cases • Limited output functions for visualisation and comparison of results • Simulations are currently simplified due to generic diesel generator with fixed efficiency
HOMER	• Industry standard for microgrid simulation • High user-friendliness due to graphical user interface • Wide range of system configurations can be simulated and optimised • Various presentations and illustrations of outputs	• Proprietary software with high license costs • Black-box simulation does not allow for detailed analysis of results • Structure of tool and simulation and optimisation algorithms cannot be changed by the user • Detailed settings need experienced users for correct application of HOMER (high barriers of entry for users)
SPT	• Excel-based user interface allows for quick understanding of tool application • Simplification of inputs and simulation algorithm allows for quick application and simulation	• Simplification reduces reliability of results • Use cases are currently limited to the Philippines

Offgridders can be seen as most suitable for academic users and planners. The advantages are that it is the most flexible tool in terms of changes and use cases and that it can be automated to simulate hundreds or even thousands of microgrids or scenarios with reasonable effort. Disadvantages lie in the higher complexity of usage, as users need to be proficient with the programming language Python if they want to add new functions. Another disadvantage lies within the simplification of the diesel genset, which may be overcome by the developers' community in the future.

HOMER is most suitable for project developers and detailed case studies. It can be seen as industry standard and is globally the most applied tool for project developers and researchers. The advantages of HOMER include the user-friendliness of the tool, as well as the many functions in terms of system settings, output tables, and illustrations. The main disadvantage of HOMER is the commercial and proprietary nature of the product. Thus, users need to pay a license fee and tool developers are not able to change the coding of HOMER and need to trust the black-box-based results.

SPT is a tool for less experienced project developers and planners. Thus, its main advantage is the simplification of inputs and calculation processes, which lowers the barriers of entry for users. Furthermore, it is implemented in Microsoft Excel, a very widespread software. The disadvantages lie also in the simplification of the tool. As only one reference week is calculated in the SPT, it remains a rough first estimate of project cost and potential. Even though the diesel gensets are simplified, results have been shown to be similar to HOMER.

In conclusion, we recommend the use of HOMER for detailed planning of projects and the SPT for pre-feasibility studies. Offgridders should be used by researchers and planners to perform a pre-feasibility analysis of a large number of locations, after which a selection of promising locations can be simulated in more detail with other tools. During application, the scientific open source community could also improve it further for future use.

3 Conclusion

Microgrids are appropriate sustainable energy solutions for remote areas in Southeast Asia. We quantify insular remote areas through a geospatial analysis and consider more than 1900 islands with a population of 7.9 million as potential locations for microgrid implementation. Such microgrids need to be based on RE to address climate change mitigation, and simultaneously need to be designed in a resilient way to address climate change adaptation. We identify solar power as most suitable for implementation on Southeast Asian islands since excellent solar resources are available throughout the region, whereas good wind potential is limited only to certain areas. This emphasises the techno-economic feasibility of solar power systems. Finally, the illustrated remoteness of many regions demands for sustainable energy systems. This implies less or even zero fuel dependency for electricity generation.

Key countries to focus on for microgrid deployment are the Philippines, Indonesia, Myanmar, and Malaysia, as these countries comprise the majority of the island landscape.

We cluster the considered islands in the population classes by the following characteristics: lower than 1000; 10,000; and 100,000 inhabitants. Microgrid deployment needs to be adapted to the characteristics of each island group. The least populated islands are characterised by few settlements with a population of around 350. Most of the islands are not yet electrified, and many communities are rather poor. Consequently, the electricity demands are small and the ability to pay for electricity is low. Overall, islands are small in area (only a few km^2) and are remotely located.

Applying different energy system modelling tools highlights that expected diesel-based power generation costs are very high for such islands, due to a large difference between peak and average load causing inefficient diesel generator operation. Hence, all applied tools project huge cost savings through RE-based hybridisation, which allows the reduction of fuel consumption. An appropriate solution for such islands could be containerised PV-battery-diesel systems, which allow for easy transportation and installation. A standardised system could be deployed for the group of more than 1200 islands comprising a population of 420,000.

Mid-sized islands have a typical population of 3000–4000. With 1.6 million, their population is four times larger than the group of least populated islands. The remoteness of such islands decreases while economic activity and island area increase compared with the aforementioned group. The modelling of RE-based microgrids for this case study group reveals cost savings and recommends installing solar capacities equal to twice the peak load (under the applied cost assumptions). For a substantial increase of renewable penetration, and thus potentially decrease of power generation costs, it is necessary to implement solar PV with battery storage, given the higher electricity demands in the evening.

The group of larger islands, in the range of 10,000–100,000 inhabitants, is comprised of only 181 islands, but is home to a large population of 5.8 million. Typically, such islands have a population of more than 35,000 with economic activities and productive use increasing the demand for electricity during the day. The assessment of RE-based microgrid options finds highest RE shares for this island class, because the electricity demand profile matches with the solar resource availability. Here, a possible implementation strategy could be to implement solar PV for fuel-saving purposes during daytime initially and then stepwise increasing solar and battery capacities to increase the RE share.

In summary, this chapter has shown the usefulness of GIS and simulation tools for planning microgrids as they enable the evaluation of the economic feasibility and environmental impact, before embarking on costly site visits to the remote islands. Different tools exist for different user needs and a focus on openly accessible tools can further enable a widespread use in the future to accelerate project development and implementation of renewable microgrids.

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