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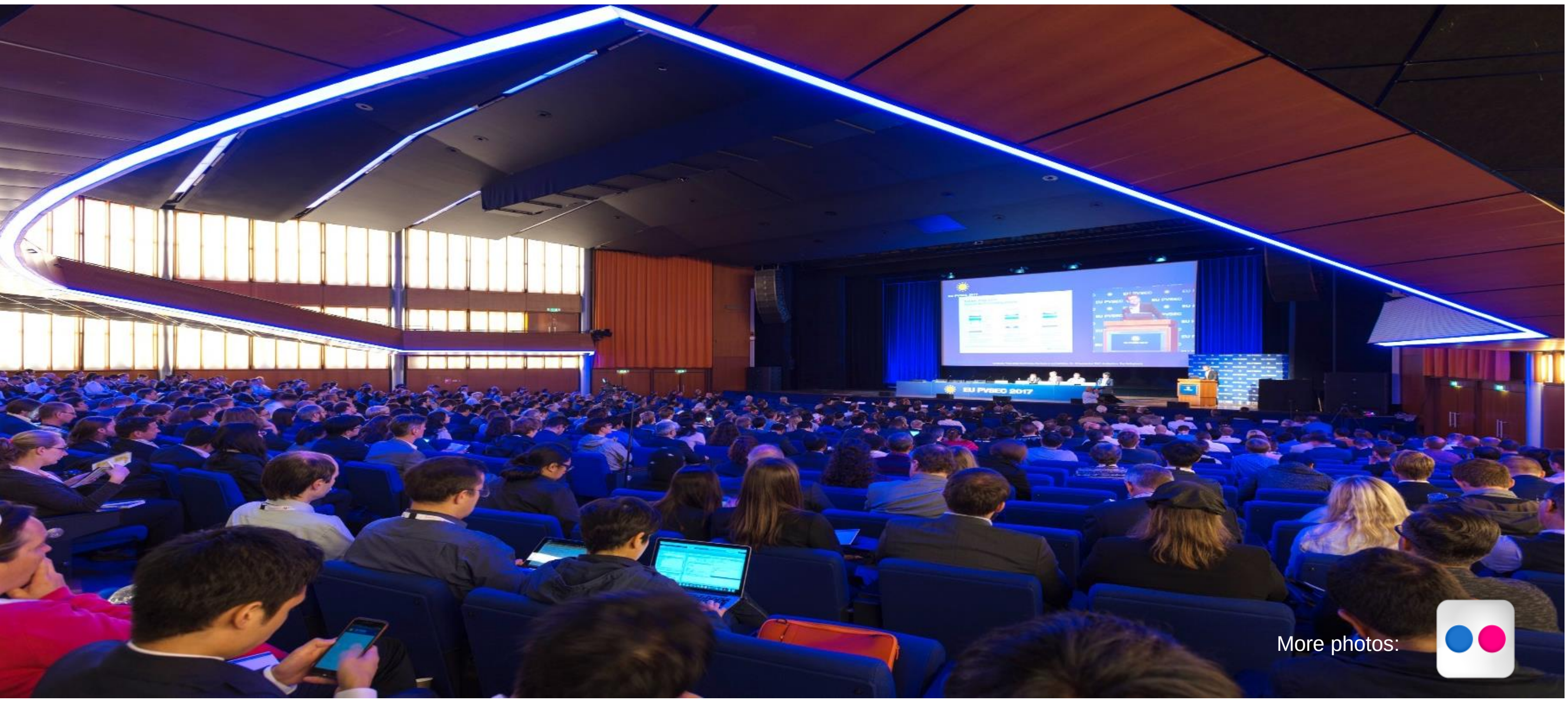

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FOREWORD

The EU PVSEC 2017 in Amsterdam concluded with the strong message that the photovoltaic revolution is just getting started. Research and innovation across the sector, together with fast deployment and numerous application options, are paving the way to putting PV at the centre-stage of sustainable energy systems. This year 2,516 participants from 89 countries took part in this most inspiring platform. It provided a vital forum for information exchange in the field of PV solar energy research, demonstration and applications. In the exhibition 64 companies from all parts of the world welcomed visitors and presented their products and services.

The EU PVSEC 2017 Proceedings give a comprehensive overview of the photovoltaic solar sector, its current status and future prospects in science, research, innovation, development and deployment on more than 4,500 pages. Selection for inclusion in the conference was made by paper review experts and topic organisers (see the listing on pages III-V), to whom we express our sincere gratitude for their comprehensive review work and overall contribution to the success of the conference. In addition to the 619 submitted papers, the proceedings include 70 presentations (slides) shown during the plenary and oral presentations as well as 232 poster files of the visual presentations. In total this amounts to 921 publications.

The 2017 EU PVSEC Proceedings maintain our commitment to providing quick and open access to high quality scientific results. They constitute a powerful tool for targeted and quick information search and retrieval, enabling you to search by keyword, paper title and authors. We are sure that these features will help to simplify the use and exploit the full potential of this extensive source of information.

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We are confident that these Proceedings will play an important role in providing a comprehensive overview of the current actors and activities in the global PV sector and that they will disseminate information on the state-of-the-art of technologies and applications. This can generate further research, add momentum to innovation and promote interest in PV worldwide.

We would like to cordially thank all authors and participants of the EU PVSEC 2017 for their contributions and look forward to welcoming you in 2018 at the 35th EU PVSEC 2018 in Brussels, Belgium.

The Editors

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2 Silicon Photovoltaics
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4 Concentrator and Space Photovoltaics
5 Performance, Reliability and Sustainability of Photovoltaic Modules and Balance of System Components
6 PV System Performance and Integration
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Session Type

P = Plenary Session
O = Oral Session
V = Visual Session

Day Codes

A = Monday, 25 September 2017
B = Tuesday, 26 September 2017
C = Wednesday, 27 September 2017
D = Thursday, 28 September 2017
E = Friday, 29 September 2017

e.g. 3CP.1 ⇒ 3=Thin Film Photovoltaics, C=Wednesday, P=Plenary Session, 1=Session 1

ESTIMATING THE TECHNICAL POTENTIAL OF GRID-CONNECTED PV SYSTEMS IN INDONESIA: A COMPARISON OF A METHOD BASED ON OPEN ACCESS DATA WITH A METHOD BASED ON GIS

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ABSTRACT: In this paper, we compare two methods for estimating the technical potential of grid-connected PV systems in Indonesia. One was a method developed by Veldhuis and Renders [1] and the other is a new method using Geographic Information System (GIS) and multi-criteria decision making (MCDM). The first method uses open access data from 2015 on a provincial level which can be applied to a complete country. Results from this method show that the total resource potential of grid-connected PV systems for all provinces in Indonesia in 2015 is 7,799 TWh which can be produced by 5,374 GWp total capacity of PV systems requiring 1.2% of the total land area of Indonesia. Because a detailed and accurate study on the technical potential of grid-connected PV systems in Indonesia is lacking, we propose another method which combines the capability of GIS and MCDM to develop a model which maps the potential of grid-connected PV systems in Indonesia. This model uses a digital elevation model (DEM) and thematic maps as inputs to produce a vector layer of calculable suitable areas for grid-connected PV systems. To validate this model, data has been collected during a field research which took place in Indonesia in Spring 2017. Also, a preliminary and more complex model for decision-making of grid-connected PV systems in Indonesia is introduced.

Keywords: potential, grid-connected PV systems, Indonesia, mathematical model, GIS, MCDM.

1 INTRODUCTION

In this paper, we compare two methods for estimating the technical potential of grid-connected PV systems in Indonesia. One method was developed by Veldhuis and Reinders [1] and has been implemented for estimating the technical potential of grid-connected PV systems in Indonesia. The other one is a new method which uses geographical information system (GIS) and-and multi-criteria decision making (MCDM). This method has not been implemented yet because it is now in the phase of concept development and it would become the first part of a full concept of developing a decision-making model for distributed solar photovoltaic (PV) systems which aims at increasing the electricity system's resilience in Indonesia. This work is part of the Ph.D. research currently undertaken at the Department of Design, Production and Management, University of Twente by the first author of this paper. Therefore, in this paper, the full preliminary and interdisciplinary concept mentioned above is also briefly introduced.

It is necessary to develop methods to estimate the technical potential of PV systems in Indonesia because - despite having a high irradiation and a favorable policy towards PV systems, the actual number of installations of PV systems in Indonesia is lagging behind the technical resource potential [4] [5]. By 2015, only 14 MWp of PV systems (both grid-connected and stand-alone systems) have been installed in Indonesia [4] which is small compared to a technical potential of 27 GWp estimated by Veldhuis and Reinders [1] using data from 2010.

Indonesia is an emerging economy with a large and is increasing energy demand. Its total area of 1.9 km^2 is divided into 34 provinces. Indonesia comprises of more than 13 thousand islands [6] in which about 4 thousand islands were inhabited in 2015 [7]. It is a tropical country which is located in Southeast Asia and Oceania (Figure 1). The population of Indonesia in 2015 was around 252

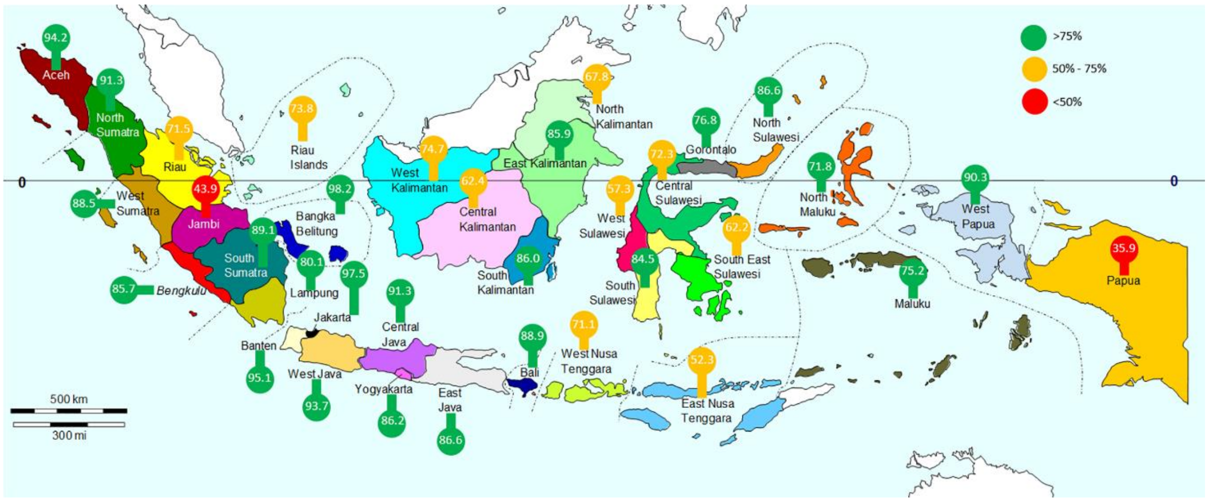

Figure 1: Map of Indonesia showing electrification ratios for 34 provinces in 2015. Data is based on PLN [2]; the map is based on Dalet [3].

million people which rank Indonesia as the fourth most populated country in the world [8].

However, Indonesia is still facing challenges in providing a sufficient, appropriately distributed, affordable, reliable, and cleaner electrical power supply to the whole population. In 2015, 11.7% of Indonesian people remained without electricity services [9] and the differences in electrification ratios (ER) inside the country are enormous (Figure 1). Also, Indonesia emits a significant and is increasing amount of CO_2 from the energy sector because the final energy consumption in Indonesia is dominated by fossil fuels [10]. Finally, the reliability of power grid in Indonesia is relatively low which is characterized by frequent blackouts and brownouts [9, 11-15].

Being located on the equator, a stable and high solar irradiation the whole year through is guaranteed. The annual average solar irradiation in Indonesia ranges from 4.4 kWh/m^2/day to 6.2 kWh/m^2/day [16] resulting in a total annual global irradiation in between 1,600 and 2,260 kWh/m^2/year depending on the location. Therefore, distributed solar PV systems are promising solutions to Indonesia's problems with the lack of electricity supply, low reliability of grid, and high CO_2 emissions. This is supported by favorable policy from the Indonesian Government which sets renewable energy (RE) target of 23% by 2020 and 31% by 2030 [17].

To stimulate the solar sector in Indonesia, it is, therefore, necessary to have a tool which could be used to carefully planning the grid-connected PV systems in Indonesia context. Such a tool should have a comprehensive approach. It should be capable to spatially locate the suitable points for grid-connected PV installations, estimate their technical potential and calculate the resulted improvement in grid reliability by considering technical and economic constraints. It should also take the social and regulatory aspects into consideration and estimate the environmental benefit from PV integration.

However, we are sure that there is no tool which has the afore-mentioned features available for Indonesia context. Most of the current studies in solar energy in Indonesia focus on off-grid PV applications. A few literatures about grid-connected PV systems in Indonesia are available. Tarigan et al. (2013) [18] evaluate the technical, economic and environmental aspects of grid-connected PV system in a typical residential in Surabaya, Indonesia using PVsyt and RETScreen software. Outhred and Retnanestri (2015) [19] evaluate the Australia's experience in developing household rooftop PV systems to provide insights to other countries including Indonesia contemplating similar scenarios. Those studies are appreciated, but issues related to grid-connected PV system potential studies and decision-making for Indonesia context are yet addressed.

In this paper, we will first introduce the method by Veldhuis and Reinders (Section 2.1) and its application based on data from 2015 (Section 2.2). In Section 3, the general concept of our new GIS-MCDM model for estimating grid-connected PV potential will be shown and a full preliminary concept of decision-making model for grid-connected PV in Indonesia will be briefly introduced. Finally, a discussion and conclusions are presented in Section 4.

2 METHOD VELDHUIS AND REINDERS

2.1 The Method

The method developed by Veldhuis and Reinders focused on estimating the resource and technical potential of grid-connected PV systems at provinces in Indonesia. This study filled the lack of literature in solar PV potential because previous studies did not distinguish between the potential of grid-connected and off-grid PV systems. Frost and Sullivan [20] reported that a total capacity of PV system for the whole Indonesia is more than 1,000 GWp. Further, a study from the Ministry of Energy and Mineral Resources of Indonesia [21] observed the PV system potential at province level with an average resolution of 300 km x 300 km.

In Veldhuis and Reinders [1] study, the mathematical model applied uses input data on a provincial level such as the population density, urbanization ratio, irradiation, electrification ratio and electricity demand. Both the resource potential and technical potential of grid-connected PV systems are determined for urban cores, suburbs and villages with population densities of respectively 5,000 persons/km^2, 1,000 persons/km^2 and 500 persons/km^2 (Figure 2). The full description of the mathematical operations in the methods of Veldhuis and Reinders can be found in their paper [1].

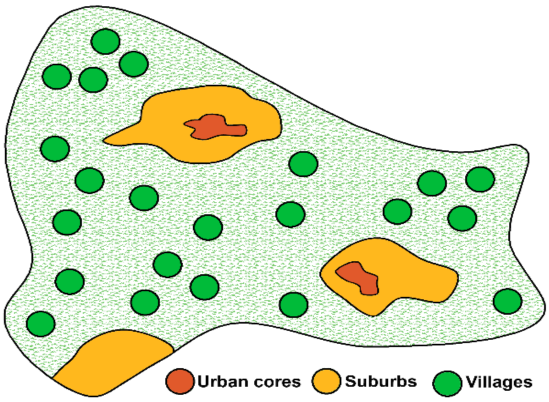

Figure 2: Schematic representation of the classification of the four areas inside a province: (1) urban core (red), (2) suburbs (orange), (3) villages (yellow), and (4) rural areas (green). Based on Veldhuis and Reinders [1].

2.2 The Results

Table I presents the results from the application of Veldhuis and Reinders's method using data from 2015. It shows the resource and technical potentials of grid-connected PV systems for all 34 provinces of Indonesia. As can be seen, the total potential of grid-connected PV systems in based on resource potential in 2015 is 5,374 GWp. The share of this potential for respectively urban cores, suburbs and village areas is 13%, 42%, and 45%. This amount of PV capacity would require 23,587 km^2 area which corresponds to 1.2% of the total land area of Indonesia.

If the above potential is limited to the electricity demand in 2015, the total technical potential of grid-connected PV systems in Indonesia in 2015, is 34 GWp. Fig. 1 shows an example of maps resulted from this method that presents the distribution of the technical potential of grid-connected PV systems (MWp) over 34 provinces in Indonesia using data from 2015. The share of this resource potential for urban cores, suburbs, and villages is resp. 30%, 39%, and 31%. This amount of PV system installed capacity would require 201 km^2 area which corresponds to 0.01% of the total land area of Indonesia.

Table I: Resource and technical potentials capacity of grid-connected PV systems for each province in Indonesia based on calculation method from Veldhuis and Reinders [1].

PROVINCE	PV SYSTEM CAPACITY (MWp) BASED ON RESOURCE POTENTIAL				PV SYSTEM CAPACITY (MWp) BASED ON TECHNICAL POTENTIAL			
	Urban core	Suburb	Village	Total	Urban core	Suburb	Village	Total
Aceh	0	54,817	129,691	184,508	0	37	87	124
Bali	0	66,257	26,769	93,026	0	369	149	519
Bangka Belitung	0	21,645	21,358	43,003	0	33	33	66
Banten	102,353	46,702	65,512	214,567	1,287	587	824	2,697
Bengkulu	0	20,586	39,707	60,293	0	14	27	41
Gorontalo	0	13,607	14,963	28,570	0	14	15	29
W. Papua	0	9,849	20,050	29,898	0	14	28	41
Jakarta	4,515	0	0	4,515	4,515	0	0	4,515
Jambi	0	26,760	11,259	38,020	0	74	31	105
W. Java	194,848	497,527	220,501	912,876	2,235	5,706	2,529	10,469
C. Java	38,804	232,018	269,446	540,268	231	1,380	1,602	3,213
E. Java	175,060	341,898	398,917	915,875	1,300	2,540	2,963	6,803
W. Kalimantan	18,280	30,575	68,072	116,927	24	40	90	154
S. Kalimantan	18,778	31,689	50,784	101,252	31	53	85	169
C. Kalimantan	0	26,105	20,888	46,993	0	42	34	76
E. Kalimantan	0	53,099	18,118	71,217	0	138	47	184
N. Kalimantan	0	7,525	238	7,763	0	113	4	116
Riau Islands	0	24,757	0	24,757	0	439	0	439
Lampung	0	80,643	167,224	247,867	0	132	274	406
N. Maluku	0	11,037	19,793	30,830	0	7	12	19
Maluku	0	19,776	21,965	41,741	0	18	20	38
W. N. Tenggara	11,281	45,178	36,632	93,090	8	32	26	67
E N. Tenggara	0	36,986	59,635	96,620	0	21	34	56
Papua	0	20,415	6,078	26,493	0	60	18	78
Riau	25,312	42,579	60,603	128,494	56	95	135	286
W. Sulawesi	0	9,929	16,913	26,841	0	5	9	14
S. Sulawesi	42,212	59,081	120,976	222,268	105	148	302	555
C. Sulawesi	0	26,967	50,665	77,632	0	14	27	42
S.E. Sulawesi	0	24,138	27,173	51,311	0	22	25	46
N. Sulawesi	0	34,713	29,072	63,785	0	56	47	103
W. Sumatra	0	71,225	80,850	152,075	0	218	248	466
S. Sumatra	0	98,558	161,061	259,620	0	204	334	538
N. Sumatra	62,641	132,609	159,569	354,819	213	450	542	1,205
Yogyakarta	8,650	44,056	13,141	65,847	35	181	54	270
INDONESIA	**702,733**	**2,263,306**	**2,407,621**	**5,373,660**	**10,041**	**13,255**	**10,653**	**33,948**

3 PRELIMINARY CONCEPT OF THE NEW MODEL

Using the method from Veldhuis and Reinders, the potential capacity of grid-connected PV systems in Indonesia can be easily estimated using open access data for the provincial or district level with the average resolution of around 100-300 km x 100-300 km. Further, it would be useful to estimate the accuracy of these studies and to increase their resolution by zooming into the level of cities with an average resolution of 15 km x 15 km or even better to the level of neighborhoods.

Because data for this purpose may not always be (made) available by local governments, it is difficult to use the method from Veldhuis and Reinders for a smaller area. Therefore, a more independent approach may be necessary in this case. Geographic Information Systems (GIS) and multi-criteria decision making (MCDM) could be a possible solution to tackle these issues and is part of our new approached that will be presented in Section 3. The GIS approach will be relevant because of ongoing efforts by government and private institutions in producing geospatial information such as digital elevation model (DEM), satelite imageries, maps, among others, for conductiong studies for the whole country.

3.1 GIS and MCDM approach

The GIS comprise sets of tools that can capture, store, retrieve, analyze and present various data which are spatially attributed to locations for a special set of purposes [22]. In short, GIS is embedded in a computer system that uses geographical data to create useful information. Maps have an essential role in GIS given its capability to store, retrieve, analyze, and present spatial data.

Based on several studies such as Khan (2014) [23], Lozano (2013) [24], Hafeznia (2017) [25], and Carrion (2008) [26], we summary the following main five steps to develop a GIS-MCDM model:

- identifying the criteria and input dataset,
- identifying appropriate software/tool that is capable of handling the previously-defined criteria,
- building the model in the GIS environment,
- analyzing the results.

1. Identifying the criteria and input dataset.

Due to multiple objectives that must be examined at the same time, making the most favorable decision could involve a complex process [24]. Some criteria are needed to ensure the judgment is measurable and quantified [26]. Like the GIS, MCDM has also been implemented in many fields [24] and therefore, they could be a good combination in this study. The MCDM is used due to its popularity in energy decision making [27] and also because it suits the complexity of factors to be considered in identifying suitable areas for grid-connected PV plants.

"MCDM refers to making decisions in the presence of multiple, usually conflicting, criteria" [28]. It is a decision support model which consists of a set of solutions, criteria and values [29]. The alternatives of the solution are ranked or sorted by the decision maker. The qualitative and quantitative of criteria are based on some predetermined indicators. The values of each alternative of corresponding criterion could be based on information from literature or an expert and stakeholder consultation.

MCDM applications in energy planning decision involve various methods. The methods are built based on priority setting, fuzzy principles, weighted averages, outranking, and their combinations [27]. In this study, we apply the weighted averages method using a set of criteria as shown in Figure 3.

2. Identifying appropriate software/tool that is capable of handling the defined criteria

Although some GIS software packages offer tremendous help in working with GIS and related tasks with their unified approaches, sometimes more than one tools are needed to tackle a problem. The selection of software depends on the objective of tasks to achieve. The general rule of thumb is that the software must be capable of creating, managing, analyzing, and visualizing geographic data. Therefore, the selected GIS software can be used as an environment to building the GIS model.

3. Analysis

The criteria previously described are used to conduct an analysis. An example from Carrion (2008 [26]) suggested that the criteria could be grouped into two classes: (i) supporting criteria, (ii) hindering criteria or restrictions. Supporting criteria are those that increase the suitability of an area for grid-connected PV plants while hindering criteria represents the negative factors that restrict an area for grid-connected PV installation.

In the next step, a final layer could be created showing areas with higher values only (have more supporting criteria), while areas with lower values (have more hindering criteria) will be removed or indicated low potential.

Figure 3 shows an example of a GIS-MCDM model which could be used for estimating the technical potential of grid-connected PV system for a city or neighborhood level in Indonesia context.

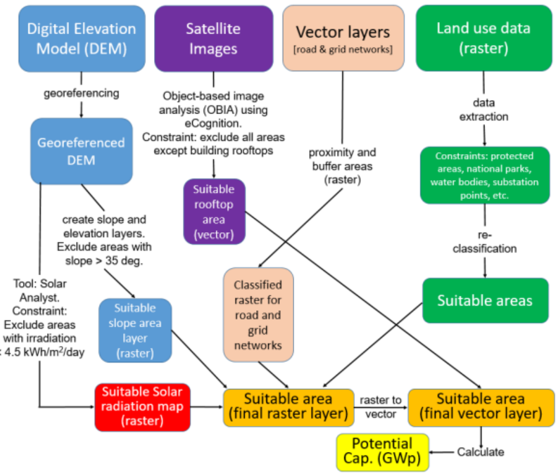

Figure 3: An example of GIS-MCDM model for estimating the potential capacity of grid-connected PV for a city or neighborhood level in Indonesia.

Initially, users define the inputs indicators for implementing the GIS and MCDM methods. Some examples of indicators are proximity to roads, unsuitable lands, harsh topography, and solar irradiation level. The model could be developed within various GIS packages such as ArcGIS from ESRI, eCognition from Trimble, QGIS from Quantum, and others. A digital surface model (DSM), vector and raster maps are examples of useful inputs

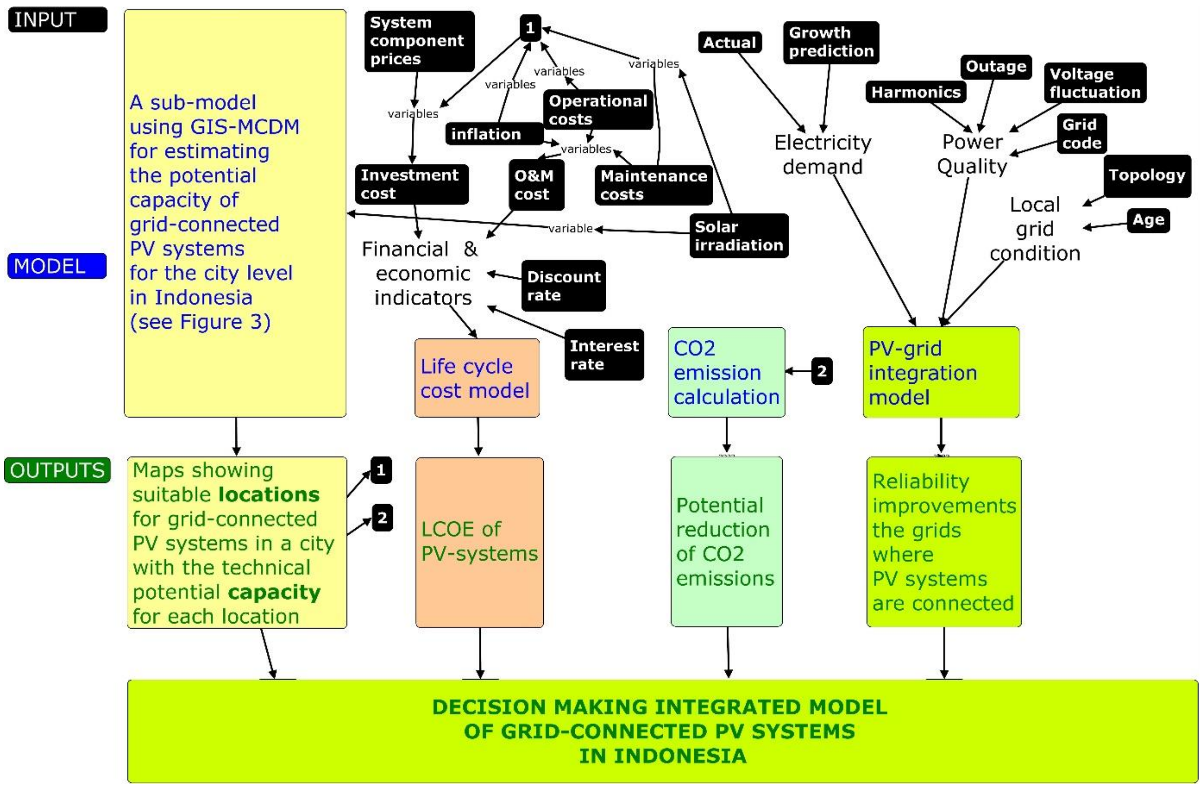

Figure 4: The full model proposed for decision-making of grid-connected PV systems in Indonesia.

for those tools that represent the area of a city which covers earth surface, buildings, roads, water bodies, open spaces, among others. Using the pre-defined indicators, a thematic layer of unsuitable areas could be created. In such a layer, only suitable areas of PV plants remain. Based on the knowledge about the suitable area and their distribution, the technical potential of grid-connected PV system could be calculated and mapped.

3.2 The Full Model

Besides estimating the potential capacity of grid-connected PV systems in Indonesia, as mentioned in Section 1, the definite function of this work is to develop a comprehensive decision-making model. The tasks of the model are to find the feasible locations for grid-connected PV plants and estimate their technical capacity, evaluate the reliability improvements on the grid to which the PV systems would be connected, and estimate the potential environmental benefit of distributed PV systems.

Figure 4 shows a general and preliminary concept of the proposed model. As can be seen, the first step of modeling is to create maps of suitable locations for grid-connected PV systems with their corresponding PV system capacity. This step could be conducted using the GIS-MCDM sub-model as shown in Figure 3. Once the capacities of PV systems are known, their values could be used to estimated the avoided CO_2 emissions using emission factors of different types of fossil fuels. Then, the levelized costs of energy (LCOE) could be calculated using life-cycle cost analysis (LCCA) based on various inputs. Finally, the improvements in the reliability of local grids by integrating PV systems could be estimated using a separate model.

4 DISCUSSION AND CONCLUSION

4.1. Grid-Connected PV potential estimation

Using data from 2015 as input for Veldhuis and Reinders method [1], it has been found that the total resource potential of grid-connected PV systems in Indonesia is about 5,374 GWp and the technical potential is about 34 GWp. The area required are 31,557 km^2 for the resource potential and 201 km^2 for the technical potential. A comparison of the results from the previous study based on data from 2010 [1] and the result from this study is described as follows: The resource potential changed by a factor of 5 and the economic potential increased by 26% following the growth of energy demand in the daytime from 2010 to 2015. The resource potential of electricity generation by PV systems in 2015 is 38 times the total electricity demand in 2015 based on data from the national utility PLN [2]. Logically the PV system capacity for resource potential increased nearly 5-fold from 1,100 GWp in 2010 to 5,374 GWp in 2015. This is due to growing population (at 1.5% per year) [30], increasing electricity demand (at 8.6% per year) [17] and increasing the PV module efficiency (from 15% in 2010 to 17% in 2015).

As shown in Figure 5, the relation of resource and technical capacities are not always linear like in Jakarta. For example, due to a large area, the resource potential in Lampung is 600 times its technical potential because of the small demand in the village and rural areas.

Table II shows a brief comparison of advantages and disadvantages of the Veldhuis and Reinders method and the GIS-MCDM model. By using the GIS-MCDM model proposed in this study, more accurate results could be expected because it can work with higher resolution input data. However, the GIS-MCDM model relies on the availability of DEM and other spatial information which is promising for the future considering the fast production of such data to date.

4.2. The New Decision-Making Model

Despite that this decision-making model offers a more comprehensive approach which considers many relevant variables, this is a preliminary concept that needs further studies. In particular, other influencing factors such should be included such as types of mounting methods, the balance of system (BOS), energy payback time, and existing grid capacity, among others. Later, after a complete development of the model, it needs to be tested and validated using more information which could take another one year to collect.

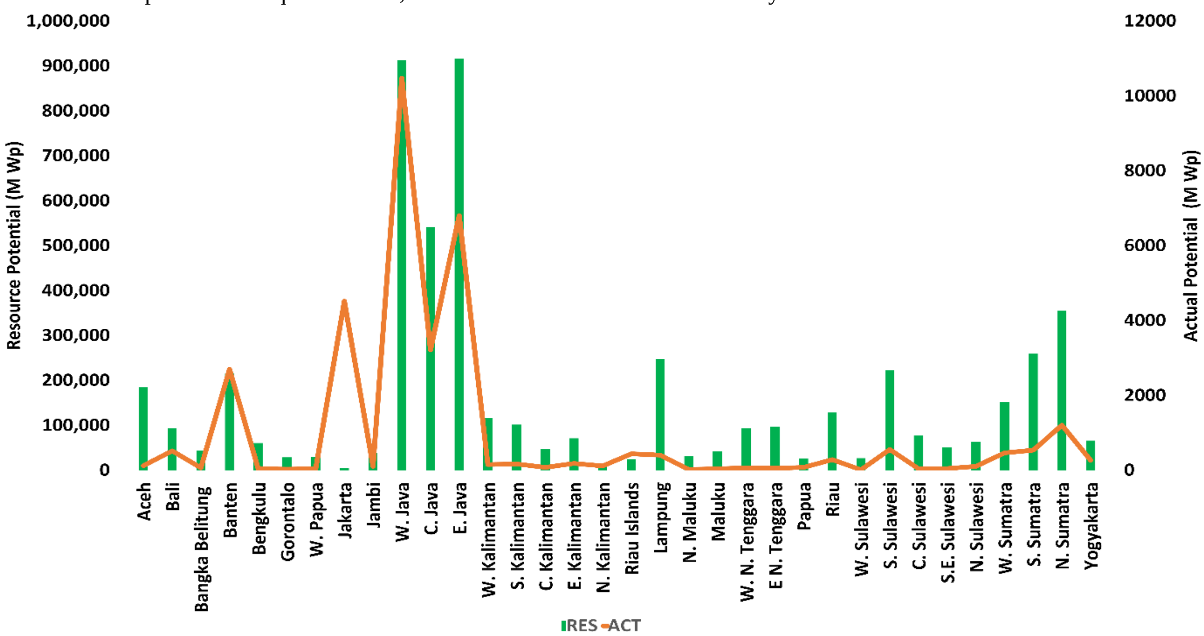

Figure 5: The technical potential of grid-connected PV systems in provinces in Indonesia based on the method from Veldhuis and Reinders.

Table II: Advantages and disadvantages of the Veldhuis and Reinders method in estimating the technical potentials of grid-connected PV systems for each province in Indonesia and its comparison to the GIS-MCDM method.

	Veldhuis and Reinders Model	GIS-MCDM model
Advantages	▪ Open access data for provincial and district levels can be used, ▪ The model is relatively simple, ▪ The model can be run on Ms. Excel, ▪ This is perhaps the first peer-reviewed work about PV potential estimation on provincial level in Indonesia.	▪ Literatures with examples from other counties are available, ▪ Higher level of accuracy and detail. It can show smaller area of cities or even neigbourhood, ▪ It could show spatial distribution of potential locations of grid-connected PV systems, ▪ It is dynamic, namely it could be used with different resolution as long as data is available
Disadvantages	▪ It cannot be used for smaller area than district level (resolution below 100 km x 100 km) because the data is not available, ▪ It does not include detail/local information, ▪ The spatial distribution of PV systems cannot be shown (lower aggregation level)	▪ Special data (not open access) are needed such as DEM, aerial imageries, maps of land use, etc. Data has not available for all locations in Indonesia yet, ▪ The model is quite complicated, requires special softwares (not for free)

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