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A spatial cost-benefit-externality modelling framework for siting of variable renewable energy farms: A case in Bohol, Philippines

Dave J. Pojadas [a, b, *], Michael Lochinvar S. Abundo [c, d]

[a] School of Engineering, University of San Carlos, Cebu City, Philippines
[b] Bohol Island State University Main Campus, Tagbilaran City, Bohol, Philippines
[c] Energy Research Institute at Nanyang Technological University (ERI@N), Ocean Pixel Pte Ltd, Singapore
[d] OceanPixel Pte Ltd, The NEST, NTU Innovation Centre, 71 Nanyang Drive, 638075, Singapore

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ABSTRACT

Site selection is an integral component of energy planning. For renewable technologies, Geographic Information System (GIS) and multi-criteria decision-making became the most prevalent approach for such a data-intensive task. However, site selection can also be carried out using GIS and Cost-Benefit Analysis (CBA). This paper aims to introduce a four-stage energy modelling framework for siting of Variable Renewable Energy (VRE) farms using GIS and CBA. Adopting a well-established framework, the first three stages are dedicated to finding suitable sites and estimating spatio-technical inputs. In the fourth stage, CBA is performed from the developer's perspective, and the viability of VRE technologies is assessed using the benefit-cost ratio. The model output is a viability map, and externalities are separately calculated to assist planning and policymaking. We implement this framework to assess the viability and estimate the externalities of utility-scale solar PV and wind farms in Bohol and find a modest potential for viable VREs in this province. The compensation effect, which is inherent to linear combination models, is unavoidable and is manifested in our results. We have also evaluated the model sensitivity to the model variables and parameters. This framework can be implemented in a study area of any geographic scale.

1. Introduction

Transitioning from fossil-based to renewable-based energy generation is without a doubt a crucial step in addressing climate change. Despite the many barriers [1], particularly in Variable Renewable Energy (VRE), the global trend is manifesting favour towards the increasing integration of renewables – evident from the rising global share of new electricity generation capacity [2], as well as the sustained investment and policy adoption [3]. The cost of constructing, operating, and maintaining Renewable Energy (RE) technologies is increasingly beating fossil-based technologies [4]. However, VRE technologies require a large area of land that may significantly impact the environment in terms of land use footprints. This is why site selection for VRE projects became one of the essential topics in the literature.

There are two common approaches in site selection of RE projects: (1) Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) or the GIS-MCDA approach and (2) GIS and Cost-Benefit Analysis (CBA) or the GIS-CBA approach. GIS is a valuable tool in planning or multiple decision-making contexts with geo-referenced data and information [5]. The selection of sites in the GIS-MCDA approach is based on criterion weights derived from decision-makers' preferences and judgments, as well as geo-referenced information of the study area. The risk of using this approach is its inability to evaluate real trade-offs generated by a policy or decision [6]. The GIS-CBA approach makes use of similar geo-referenced information and relevant economic inputs as well. While this approach cannot catch the effects of intangible aspects of a policy or decision [6], it can be more intuitive, at least from the economic perspective. For instance, a viability map that characterizes the RE resources in a study area in terms of Benefit-Cost Ratio (BCR) or Net Present Value (NPV) can be more intuitive for RE developers than a suitability map created using the GIS-MCDA approach.

Another downside of the GIS-MCDA approach is that some of its variants need data normalization technique to complete the site selection process. For instance, using Analytical Hierarchy Process

* Corresponding author. School of Engineering, University of San Carlos, Cebu City, Philippines.
E-mail addresses: djpojadas@gmail.com (D.J. Pojadas), mike@oceanpixel.org (M.L.S. Abundo).

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in criteria weighing and Weighted Linear Combination (WLC) for aggregating scores, which is the most common amongst this approach [5], requires reclassification of data. In addition to uncertainties in the judgments or preferences of decision-makers, reclassifying the input data into a new set only introduces more uncertainty to the results. GIS-CBA approach does not need any normalization technique and may produce a less uncertain result.

There are also assumptions in the GIS-MCDA approach which can be validated in the GIS-CBA approach. For instance, restricting the suitability of VREs to a certain threshold distance from transmission lines and road network appeared a common practice in several GIS-MCDA studies [7–13]. In GIS-CBA, it is possible not to consider any of these threshold distances and allow the model to identify the distance at which a solar PV or a wind farm can be regarded as viable - justifying the extension of transmission and road infrastructure.

GIS-MCDA approach became more popular in selecting sites suitable for RE because it is simpler and more straightforward. Nevertheless, evidence of GIS-CBA studies can be traced in the literature [14–17]. Based on monetization and inter-temporal discount [6], CBA is often used as a tool to assess investments in terms of infrastructure, and money is the unit of measure. In the context of energy, the NPV, BCR, and Internal Rate of Return (IRR) can be used as control variable for any CBA framework [18]. For instance, Grilli et al. [16] introduce a novel methodology for the optimal use of forest biomass for energy purposes using NPV. However, they have neglected the costs for access road construction, and the grid connection cost is incorporated in the initial investment cost, not considering the length of the spur line in the cost-benefit model. Kim et al. [17] analyzed the feasibility of offshore wind farms in the southwest coast of South Korea, considering social and environmental indicators in identifying suitable areas. However, they did not include any social and environmental indicators in their financial model. Sun et al. [15] used GIS and economic feasibility study to evaluate the comprehensive potential for solar PV generation using NPV and simple payback period. However, the costs associated with the construction, operation and maintenance of transmission infrastructure and access roads was neglected. In our model, we have not only considered length of spur line and access road as variables, but we have also calculated the positive externalities in terms of potential local job creation and carbon emission reduction.

Aside from the fundamental CBA control variables such as BCR, NPV and IRR, the Levelized Cost of Energy (LCOE), which is the most common metric for comparing energy generation technologies, has been used in some studies. For instance, Rodrigues et al. [14] have estimated the NPV, IRR, and LCOE of potential wind farms in Terceira Island. Deshmukh et al. [19] have shown how to calculate the LCOE of wind farms, utility-scale solar PV, and concentrated solar power considering costs associated with the construction, operation and maintenance of spur line, access road, and generator in India. Castro-Santos et al. [20] have used physical spatial restrictions in a GIS tool and economical tool to obtain the LCOE of wave energy converters in Portugal's physically restricted coast areas. Rhodes et al. [21] developed and applied in Continental US a geographically-resolved method to calculate LCOE for new power plants, including RE, and internalized the environmental externalities (in terms of potential damages due to carbon emissions and air pollutants) in the LCOE models. In our model, externalities are separately estimated under the assumption that certain entities are interested in it while others are not.

This study aims to introduce a spatial energy modelling framework based on CBA and GIS, which can assess the viability of VRE technologies in a study area. Viability is measured in terms of BCR, and the model output is a viability map, analogous to GIS-MCDA's suitability map. CBA is performed from the developer's perspective. In this case, costs associated with the construction, operation, and maintenance of the power plant, spur line, and access road are incorporated in the model. Only revenues derived from the project's estimated energy generation are considered a benefit. Externalities are separately calculated to provide the government entities and the public with more understandable information in their respective interests. By doing so, the modelling results in this framework can inform planning and policymaking.

Our study contributes to the existing literature in four ways. First, to the best of our knowledge, BCR has not been used to produce a viability map and then identify viable sites for VRE projects. Second, we introduce an energy modelling framework capable of providing the appropriate information for the right audiences. Third, we investigate the compensation effects amongst model variables and compensation effect between technologies and study the impact of applying (or not applying) variable thresholds. Lastly, we also investigate the effects of the selling price, power density assumptions and land-use constraints on the viability of VREs in our study area.

2. Methodology

We build our methodology from the adoption made by Deshmukh et al. [19] to the Multi-criteria Analysis for Planning Renewable Energy (MapRE) [22]. MapRE is a multi-stage spatial energy system modelling framework developed by the Lawrence Berkeley National Laboratory [22] to identify and comprehensively value high-quality wind, solar PV, and concentrated solar power resources. It was created to map and characterize solar and wind energy zones in 21 countries in the Southern African Power Pool and the Eastern Africa Power Pool [23] and was also implemented in Bangladesh [24]. In our adoption, we introduce a four-stage spatial energy modelling framework that can be used to assess the degree of viability of VRE technology individually and conjointly (see Fig. 1). The first stage consists of the assessment of resource quality and identification of suitable sites. In the second stage, the study area is divided into smaller spatial units of analysis called Project Opportunity Areas (POAs) using a uniform grid. The third stage includes estimating spatial POA attributes such as distance from road and transmission infrastructure and resource quality (i.e., Global Horizontal Irradiance (GHI), wind speed) using the zonal grid analysis. In the fourth stage, we performed CBA to all POAs and used the BCR to classify them into four: non-viable, marginally viable, viable, and highly viable. Externalities such as carbon savings and job creation are estimated separately to inform energy planning and policymaking (see Section 2.1).

2.1. Cost-benefit-externality model

Fig. 2 depicts the cost-benefit-externality model, which can be used to assess the viability and estimate the externalities of VRE technologies in a study area. Model inputs can be characterized into technical (i.e., capacity, energy generation, length of spur line), economic (i.e., capital cost, operation cost), or external (i.e., employment factors, emissions). Technical inputs are relative to the geographic location of the POA and can be obtained in the first three stages of the MapRE (Fig. 1). External and economic inputs from various sources are exogenously applied to the model.

Because the number of model inputs is quite many and their sources come with varying degree of uncertainty due to the many diverse assumptions, the model output is uncertain to some extent. For instance, the capital costs of the spur line, road and power plant construction vary widely due to onsite realities. Estimates of power density and capacity factor parameters are also subject to a certain

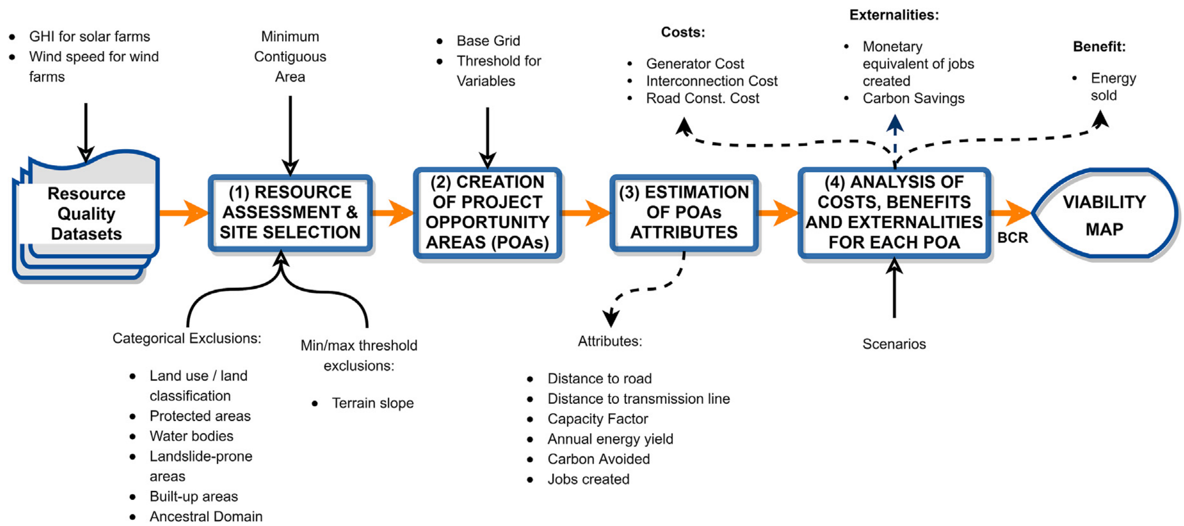

Fig. 1. The proposed energy modelling framework, adopted from MapRE [22].

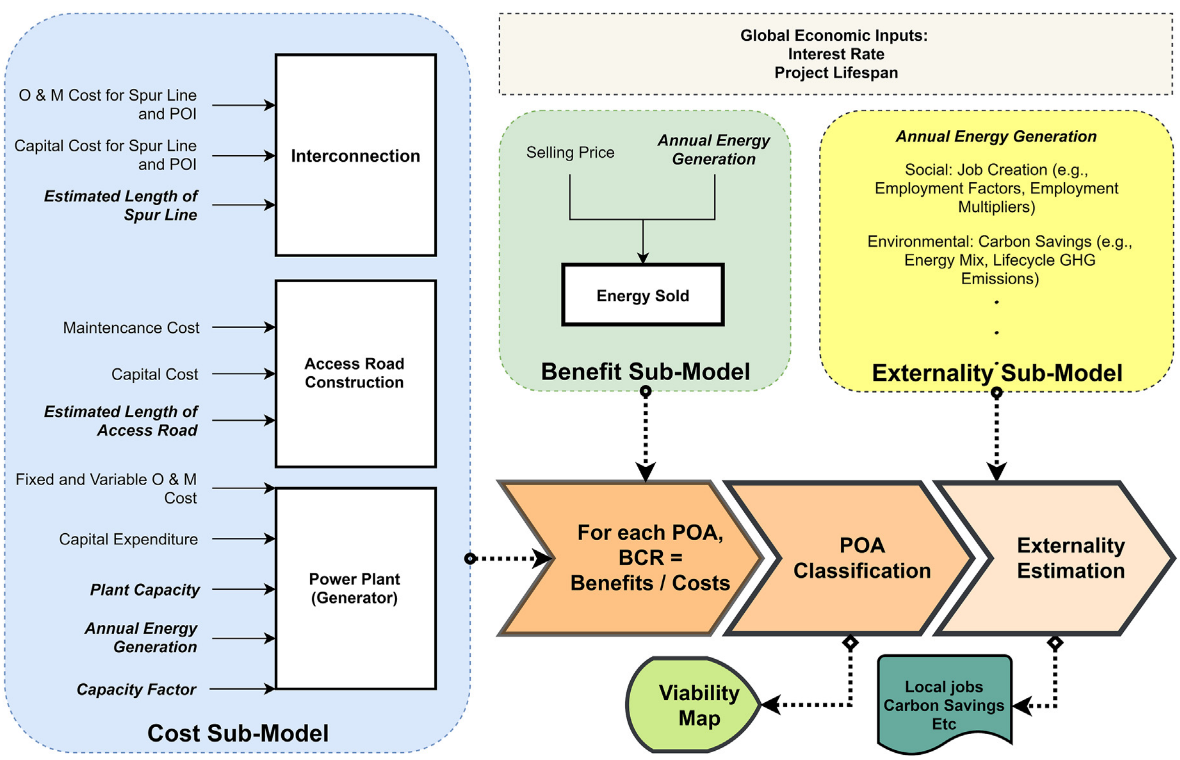

Fig. 2. The cost-benefit-externality modelling framework for siting VRE power plants. Model inputs: obtained in the spatial analysis (bold italicized texts), non-spatial (normal texts), model outputs: viability map, externality estimates.

degree of variations. Nevertheless, the model can be used to investigate the effects of any input on the viability of VREs in the study area using scenario-based or sensitivity analysis. In this study, we choose to primarily investigate the impact of technical (spatial) inputs on the viability of VRE. Raw spatio-technical inputs include the estimated length of the spur line l_j^{SL} and access road l_j^{rd}, resource quality $q_{j,k}$ (wind speed or insolation), and the relative technology-to-POA coverage $A_{j,k}$. The BCR of any POA can be expressed as a function of these four variables (see Eq. (1)). The rest of the inputs were considered parameters. NPV, which is the difference between the present values of the total POA costs and benefits, can also be calculated as a reference for developers, government entities and the public (Eq. (2))

$$BCR_j = f\left(l_j^{SL},\ l_j^{rd},\ A_{j,k},\ q_{j,k}\right) \quad \forall\ j \in J, \forall\ k \in K \qquad \text{(Eq. 1)}$$

$$NPV_j = B_j^T - C_j^T \quad \forall\ j \in J, \forall\ k \in K \qquad \text{(Eq. 2)}$$

As the ratio of the present values of total discounted benefits and total discounted costs of developing a particular POA into an energy generation project, BCR can also be estimated using Eq. (3).

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$$\boldsymbol{BCR_j} = \boldsymbol{B_j^T} \Big/ \boldsymbol{C_j^T} \tag{Eq. 3}$$

For each POA, the present values of total benefits and total costs can be estimated using Eq. (4) and Eq. (5).

$$\boldsymbol{B_j^T} = \sum_K \sum_{n=1}^{N} \frac{(\mathrm{Tarr}_k)\left(\boldsymbol{AEG_{j,k}}\right)}{(1+\mathrm{i})^{\mathrm{n}}} \tag{Eq. 4}$$

$$\boldsymbol{C_j^T} = \mathrm{I}_{\mathrm{POI}}^{\mathrm{cap}}\boldsymbol{P_j} + \mathrm{I}_{\mathrm{SL}}^{\mathrm{cap}}\mathrm{P_j}\boldsymbol{l_j^{SL}} + \mathrm{I}_{\mathrm{rd}}^{\mathrm{cap}}\boldsymbol{l_j^{rd}} + \sum_K \mathrm{I}_{\mathrm{k}}^{\mathrm{cap}}\boldsymbol{P_{j,k}} + \sum_{n=1}^{N}\frac{\mathrm{I}_{\mathrm{rd}}^{\mathrm{OM}}\boldsymbol{l_j^{rd}}}{(1+\mathrm{i})^{\mathrm{n}}} + \sum_{n=1}^{N}\frac{\mathrm{I}_{\mathrm{SL}}^{\mathrm{OM}}\mathrm{P_j}\boldsymbol{l_j^{SL}}}{(1+\mathrm{i})^{\mathrm{n}}} + \sum_{t=1}^{N}\frac{\mathrm{I}_{\mathrm{POI}}^{\mathrm{OM}}\boldsymbol{P_j}}{(1+\mathrm{i})^{\mathrm{n}}} + \sum_K\sum_{n=1}^{N}\frac{\mathrm{I}_{\mathrm{k,n}}^{\mathrm{fOM}}\boldsymbol{P_{j,k}}}{(1+\mathrm{i})^{\mathrm{n}}} + \sum_K\sum_{n=1}^{N}\frac{\mathrm{I}_{\mathrm{k,n}}^{\mathrm{vOM}}\boldsymbol{AEG_{j,k}}}{(1+\mathrm{i})^{\mathrm{n}}} \tag{Eq. 5}$$

The first four components of Eq. (5) correspond to the capital expenditures (CAPEX) in developing a given POA into a VRE farm; the rest corresponds to the operation and maintenance (O&M) costs. This equation is based on the estimation concept used by Andrade and Baldick [25], where new generation costs are only associated with the generator, spur line, and point of interconnection (POI). From the developer's perspective, costs for the possible upgrade in the bulk transmission system are excluded because other entities shoulder them. In reference to Deshmukh et al. [19], costs for access road construction are also included in the model. Other attributes which can be derived from raw attributes are shown in Eqs. (6) and (7). Please see Appendix B for the symbol description.

$$\boldsymbol{P_j} = \sum_K \boldsymbol{P_{j,k}} \tag{Eq. 6}$$

$$\boldsymbol{AEG_{j,k}} = 8760\mu \boldsymbol{P_{j,k}}\boldsymbol{CF_{j,k}} \tag{Eq. 7}$$

2.2. Compensation effect and variable thresholds

Every term of Eq. (4) and Eq. (5) is a product of economic and spatio-technical inputs. When the former is parameterized, these equations resemble the WLC model, the most commonly used method in aggregating scores for GIS-MCDA suitability analysis [26]. In this case, the economic inputs can be comparable to criteria weights, and the spatio-technical inputs are similar to the criteria scores. Thus, the compensation effect [5], which is inherent to this type of model, is inevitable. GIS-MCDA studies usually resolve this effect by applying threshold values to criteria such as distance to road or transmission line, wind speed, insolation, and area. In our model, the application of thresholds is a vital step to avoid the worst possible effects of compensation amongst variables and between technologies. For resource quality, especially for wind speed, application of threshold is a strict requirement because we do not want the model to compensate low wind speed with distances to road and transmission line or vice versa (more so with highly viable solar PV farms) and yield a technically trivial result. Costs associated with road and transmission lines construction can be outperformed by resource quality [27], justifying the extension transmission and road infrastructure. On the flip side, it is not technically feasible to construct a utility-scale wind farm in an area where the average wind speed is below 5 m/s at 80m or 100m height, no matter how distant it is from the road network or transmission infrastructure.

In the literature, the threshold value for resource quality varies across countries. For instance, land surfaces with an annual average GHI below 1700 kWh/m^2 were excluded from the analysis of potential PV hotspots in Tanzania [11], 1400 kWh/m^2 in West Bengal, India [28], and 1200 kWh/m^2 in Central Anatolia, Turkey [29]. Aside from the differences in the available resources across these countries, this variation of threshold values can be attributed to the lack of standard threshold value for solar resource quality. Thus, for study areas with relatively uniform insolation, the threshold value for GHI can be optional. Meanwhile, threshold values for wind speeds also varies (3.5 m/s [30,31], 4.5 m/s areas [32], 4.8 m/s [33], 5.5 m/s [34], and 6.0 m/s [35]). Wind turbines are designed for specific wind classes, so threshold assumptions for wind speed must be considered strictly.

Meanwhile, applying a threshold for relative technology-to-POA coverage limiting the project size is also optional because relatively small projects are easily eliminated when Eqs. (3)–(5) are applied. Threshold values for the length of spur line and access road are of particular interest. Unlike wind speed which is already limited by wind regime, there is no universally agreed threshold for these variables in the literature. In implementing this model, we choose not to apply any threshold for the length of spur line and access road to investigate the extent to which a VRE project can be viable with respect to these locational constraints.

3. Case study

We implemented this energy modelling framework to identify viable and highly viable grid-connected utility-scale solar PV and wind farms in Bohol province. Bohol is one of the 81 provinces of the Philippine archipelago. Including its islands, Bohol is approximately 4000 km^2, with 1,313,560 people living in more than 288,000 households [36]. It is composed of 47 municipalities and a lone city, Tagbilaran. Its main island, the study area, is approximately 3784 km^2 (see Fig. 3). Due to the limited word count, we submitted the documentation of the model's implementation in Bohol province as Supplementary Material (see Appendix A). That document contains assumptions and information pertinent to the province. When referring to a table or figure in that document, we use a “CS” field prefix in the following sections (i.e., Table CS-1, Figure CS-1).

4. Results and discussion

4.1. Technical potential of solar PV and wind

This study finds that, besides legal, environmental, and techno-economic exclusions, there is a modest potential for utility-scale grid-connected wind and solar PV farms in Bohol. Our assumptions of exclusion factors (Table CS-3) resulted in 51 km^2 and 31 km^2 of potential solar PV and wind farms, respectively. These areas are respectively 1.34% and 0.83% of the province's main island land surface.

Solar PV suitable areas are unevenly distributed across the province in 489 POAs (see Fig. 4-a) and can roughly generate between 1786 and 3323 GWh of clean electricity annually - almost three times and over five times the province's 2030 demand at 600 GWh [37]. 37 out of 47 municipalities have this potential, the top 3 (Balilihan, Ubay and Danao) of which comprises 30% (15.1 km^2) of the total. A portion of forestlands, uninhabited areas, and alluvial plains in the municipality of Balilihan and large alluvial plains in the municipality of Ubay became the top largest areas. Approximately 10 km^2 of forestlands, along the municipalities of

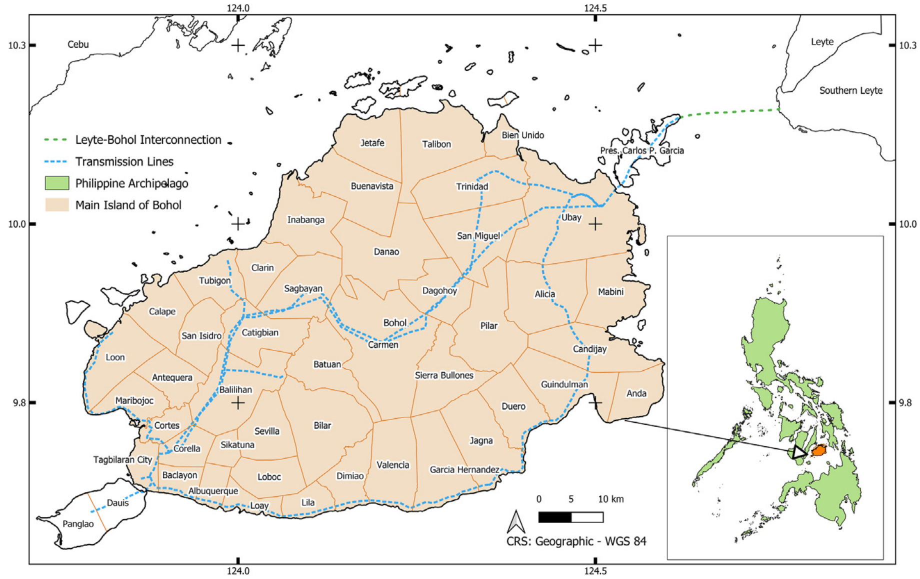

Fig. 3. The study area: the main island of Bohol province.

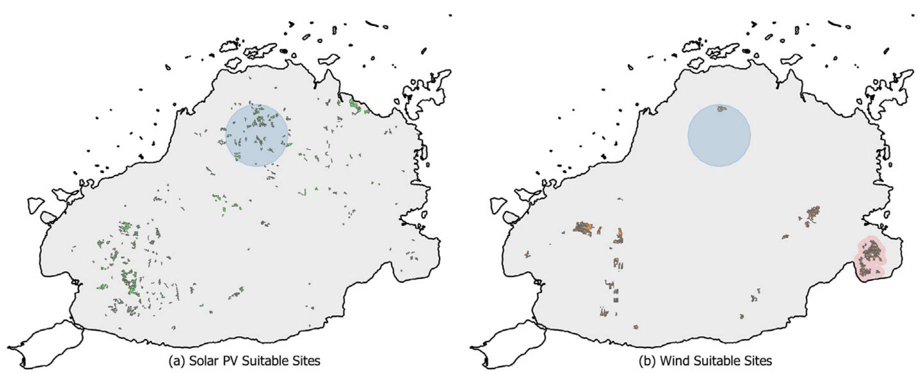

Fig. 4. Suitable sites for solar PV and wind farm. Blue circles: approximate CREZ area. Pink overlay: Anda-Guindulman-Candijay wind farm.

San Miguel, Danao, Trinidad, Talibon, Getafe, and Buenavista (blue circle overlay in Fig. 4-a), are close to the Competitive Renewable Energy Zone (CREZ) project [38]. Around 500 MW (high power density assumption) of suitable solar PV farm are found in these areas, similar to the capacity identified in the CREZ study [38].

Meanwhile, suitable wind farms are more concentrated than solar PV projects. They are found mostly in the forestlands of Anda, Guindulman and Candijay, and alluvial plains and forestlands of the municipalities of Alicia, Balilihan, Sevilla, Sikatuna, San Isidro and Catigbian (see Fig. 4-b). Wind speed in these areas varies from very low to medium. These wind farms comprised of 120 POAs can generate between 173 and 578 GWh of electricity annually – more than a quarter and almost equal to the 2030 demand of the province [37]. Only 11 MW (high power density assumption) of suitable wind farms of very low wind class are near the CREZ project [38]. This capacity is very low compared to the 400 MW identified in the CREZ study and is attributed to the restriction and buffers made for water bodies.

4.2. Viability of VREs

Because we assessed solar PV and wind viability individually and conjointly, we present our results accordingly (see Figs. 5–7). Generally, there is potential for viable (1.5<BCR≤2.5) and highly viable (BCR>2.5) solar PV and wind farms in Bohol, especially when the energy generated is paid at a subsidized selling price (Scenarios 1 and 3). However, it appeared that solar PV is not a good investment when its generation is paid below 5 Php/kWh (unsubsidized). Fig. 5 shows that only marginal (1<BCR≤1.5) and non-viable POAs are available in the province under Scenarios 2 and 4. Meanwhile, wind farms can be established in the forestlands found in the municipalities of Anda, Guindulman, and Candijay in all scenarios (see Figs. 6 and Figure 4-b pink overlay). The total capacity of these wind farms is approximately 74 MW - slightly higher than the proposed 50 MW wind project in that area [39]. Wind farms in other POAs can also be viable at a subsidized selling price. When solar PV and wind projects are analyzed conjointly, many viable POAs are possible when energy generation is paid at a subsidized selling price (Fig. 7). Other POAs can be viable in an unsubsidized selling price, provided that it is found in an area with medium wind speed.

4.2.1. Effects of selling price and power density on the viability

In all three cases, the selling price of electricity has a significant effect on the viability of POAs. When energy generated is paid under hypothetical Feed-in Tariff (FiT) Program (Scenarios 1 and 3), the number of non-viable and marginally viable POAs are only few, especially for solar PV and conjoined PV/wind (see Figs. 5–7). The

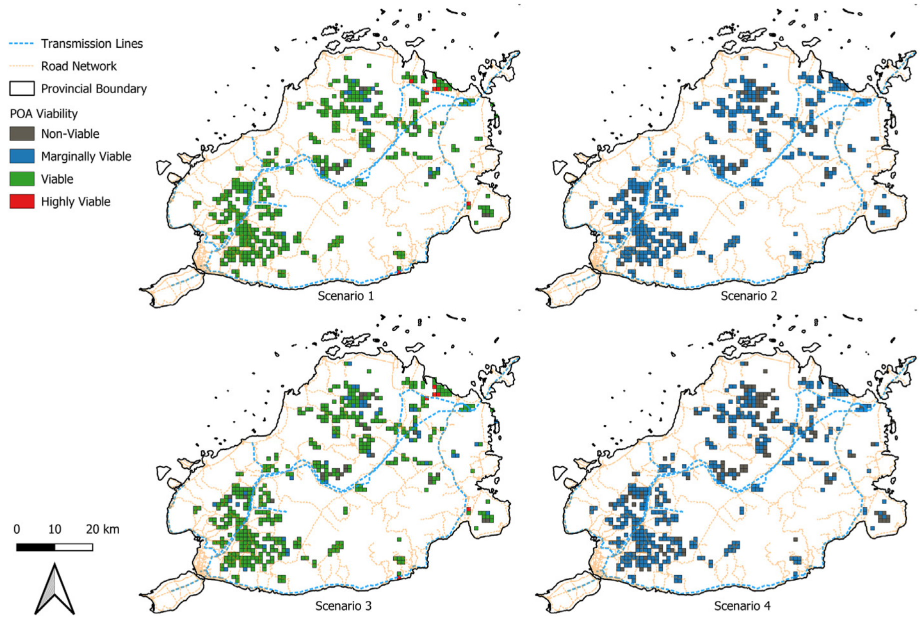

Fig. 5. Viability map for solar PV farms in Bohol province in four scenarios.

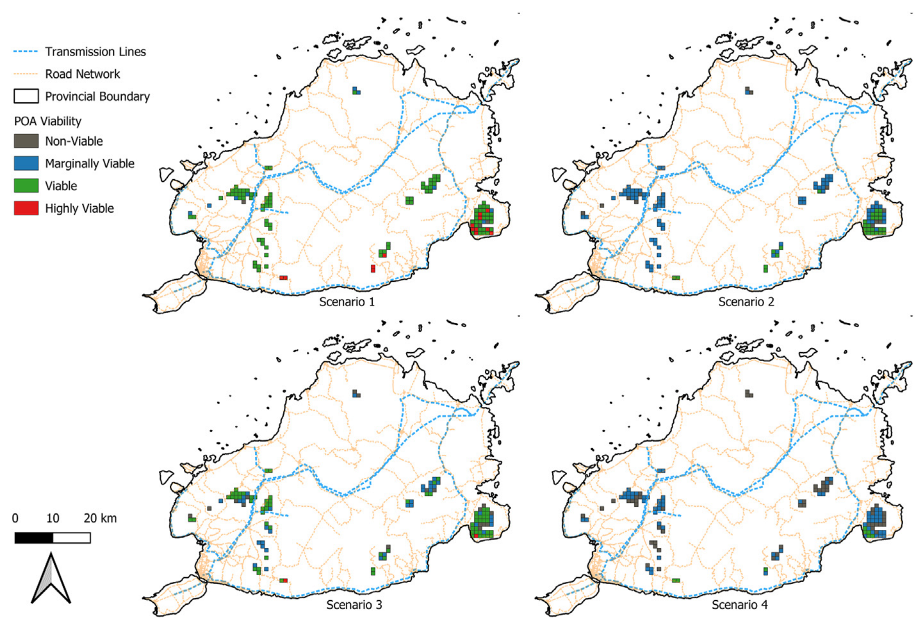

Fig. 6. Viability map for wind farms in Bohol province in four scenarios.

majority of POAs are viable, while some are highly viable. The 2030 demand for Bohol in these scenarios can be meet with the energy generation of all viable and highly viable POAs except for the low power density assumption of the wind case (see Table 1). However, when the energy generated is paid in accordance with the long-term average effective spot settlement price (Scenarios 2 and 4), the vast majority of POAs in all three cases are marginally viable (See Figs. 5–7). For solar PV case, no POA is viable when energy is paid below 5 Php/kWh (see Table 1). These results suggest that the most compelling choice if the government wanted to see solar panels and wind turbines in its soil is to subsidize the solar PV and wind projects.

On the other end, the power density assumption moderately affects the energy generation and, subsequently, the costs, benefits and externalities of every POA. The ratios of high to low power densities for solar PV and wind are 1.86 and 3.33, respectively. This can be verified in the total energy generation of all POAs in the respective scenarios of Table 1. However, each POA class's ratio of energy generation in the corresponding scenarios deviates from this rule. This is so because when the power density assumption is varied, some terms of the cost component (Eq. (5)) of the BCR equation (Eq. (3)) remains constant. Those constants are reducing (or increasing) the BCR as the power density is reduced (or increased). This can be seen in the increased number of non-viable POAs in all scenarios in all three cases of the study as the power density is reduced (see Fig. 8). In support of Obane et al. [40], it is therefore essential that future research should aim to produce a database for actual power densities of solar and wind technologies.

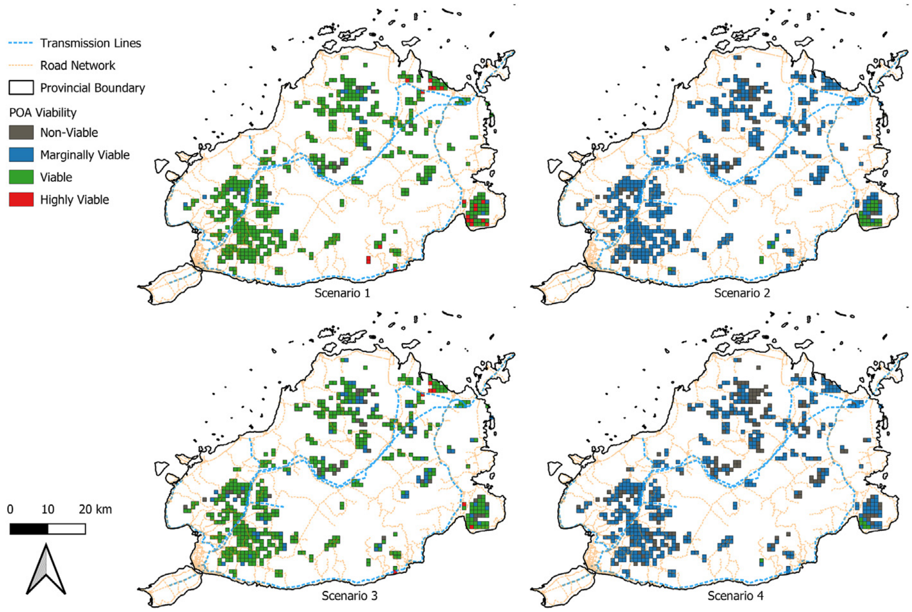

Fig. 7. Viability map for solar and/or wind farms in Bohol province in four scenarios.

Table 1
Per POA class energy generation (GWh). Assumptions: land-use constraints included, minimum project size and wind speed threshold applied.

POA Class	Solar PV Case				Wind Case				Solar PV/Wind Case			
	Scen1	Scen2	Scen3	Scen4	Scen1	Scen2	Scen3	Scen4	Scen1	Scen2	Scen3	Scen4
Non-Viable	13	100	15	168	2	22	9	53	12	104	19	182
Marginal	25	3223	56	1618	19	359	44	107	30	3574	78	1765
Viable	3195	–	1675	–	460	198	115	14	3677	223	1818	12
Highly Viable	90	–	40	–	97	–	5	–	181	–	43	–
Total	3323	3323	1786	1786	578	578	173	173	3901	3901	1959	1959

Note: Scenarios 1 and 3 have equal total energy generation because the assumptions of power densities are equal, so are Scenarios 2 and 4.

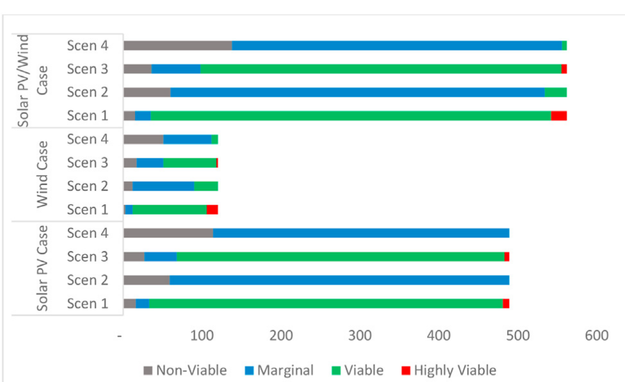

Fig. 8. POA count in all cases and scenarios.

4.3. Costs, benefits and externalities of viable and highly viable POAs

In our model, costs and benefits, including NPV, varies primarily with spatio-technical inputs such as length of spur line and access road, resource quality, and relative technology-to-POA coverage because all economic inputs are parameterized. Externalities only vary with energy generation, in which the origin can be traced to resource quality. The modelling results shown in Table 2 can inform developers, policymakers and the public about the potential costs which can be incurred, the benefits which can be accumulated, the jobs which can be generated, and the carbon savings when all or a fraction of viable and highly viable POAs in the study area are developed. It is worth noting that the monetary equivalent of job creation is a component of costs associated with the construction, operation, maintenance and decommissioning of power facilities. The jobs created in the construction and maintenance of access road are not included. Carbon revenue can also benefit developers, especially in countries with carbon trading markets or renewable portfolio standards.

4.4. Land use constraints

Siting of solar PV and wind farms in the Philippines is mainly constrained by land-use policy. In Bohol, land use constrained areas occupy around 53.6% (2026 km^2) of the main island's land surface. If the land-use constraint is relaxed, the total suitable solar PV and wind areas increase to 202 km^2 and 63 km^2, respectively. Relaxing the land use constraints doubled the number of potentially viable and highly viable wind projects in Bohol province (see Table 3). With this, approximately half of the province's 2030 demand can be met with wind technology without subsidizing the energy. This insight can be important for an agricultural province pursuing wind energy to supplement its electricity supply. Wind technologies have relatively low land-use footprints. They can be established in agricultural areas occupying a small fraction of plant area, leaving the rest for agricultural use [18], as opposed to solar PV, which significantly impacts land use to the point of land conversion.

Table 2
Costs, benefits, and externalities of viable and highly viable POAs at BCR limit of 1.5. Assumptions: land-use constraints included, minimum project size and wind speed threshold applied.

		Total Costs, million Php	Total Benefits, million Php	Total NPV, million Php	Local Jobs		Annual Carbon Savings	
					Number of Jobs	Monetary Equiv., million Php	Amount, tCO2e	Carbon Revenue
Solar PV Case	Scen1	181,324	402,351	221,026	85,697	34,279	2,648,556	19,332
	Scen2	–	–	–	–	–	–	–
	Scen3	97,184	210,061	112,876	44,755	17,902	1,382,767	10,093
	Scen4	–	–	–	–	–	–	–
Wind Case	Scen1	28,834	58,021	29,187	3938	1575	467,430	3412
	Scen2	8178	13,758	5580	1121	448	166,031	1212
	Scen3	6804	12,545	5741	820	328	101,066	738
	Scen4	578	955	376	81	32	11,519	84
Solar PV/Wind Case	Scen1	209,939	462,279	252,340	89,868	35,947	3,130,387	22,848
	Scen2	9499	15,536	6037	1927	771	186,281	1360
	Scen3	104,809	225,389	120,579	45,852	18,341	1,505,580	10,989
	Scen4	534	856	322	107	43	10,262	75

Table 3
Per POA class energy generation (GWh), land use constraints relaxed.

POA Class	Solar PV Case				Wind Case				Solar PV/Wind Case			
	Scen1	Scen2	Scen3	Scen4	Scen1	Scen2	Scen3	Scen4	Scen1	Scen2	Scen3	Scen4
Non-Viable	18	171	24	273	2	23	10	64	16	171	29	290
Marginal	56	13,190	83	6907	21	798	54	241	60	13,934	107	7200
Viable	12,751	–	6881	–	930	308	259	33	13,632	385	7169	28
Highly Viable	536	–	192	–	177	–	16	–	783	–	213	–
Total	13,361	13,361	7179	7179	1130	1130	339	339	14,491	14,491	7518	7518

Table 4
The longest length of spur line and access road and lowest wind speed calculated for the study at a BCR limit of 2.0 in Scenario 1. Assumptions: land-use constraints included, minimum project size and wind speed threshold applied.

	POA ID	Solar PV Area, km^2	Annual GHI, kWh/m^2	Wind Area, km^2	Wind Speed, m/s	Length of Spur Lines, km	Length of Access Road, km	BCR
Solar PV Case	4633	0.062	1716	–	–	22.75	0.05	2.27
Wind Case	8323	–	–	0.049	7.842	9.91	0.59	2.33
Solar PV/Wind Case	4633	0.062	1716	–	–	22.75	0.05	2.27
Longest access road, km								
Solar PV Case	5242	0.271	1715	0.442	5.558	13.66	5.21	2.08
Wind Case	8232	0.055	1819	0.579	6.909	7.14	4.12	2.40
Solar PV/Wind Case	5242	0.271	1715	0.442	5.558	13.66	5.21	2.01
Lowest wind speed, m/s								
Wind Case	3269	0.453	1636	0.638	5.764	3.19	0.16	2.00
Solar PV/Wind Case	2483	0.021	1626	0.037	5.552	5.90	0.05	2.11

4.5. Co-location of solar PV and wind farms

Due to the similarities in the exclusions and restrictions used in finding suitable sites (Table CS-3), there is a possibility to co-locate solar PV and wind farms in Bohol. To find areas suitable for co-location, we calculated the overlap of solar PV POAs over the wind POAs (and vice versa). POAs with an overlap percentage over 50% in the two analyses are considered potential areas for co-location. The results suggest that there is no enough POA contiguity to consider co-location when the land-use constraint is applied (see Fig. 9-a). Most areas with wind speed above 5.5 m/s are located in mountainous forestlands where terrain slope is greater than 10%, so they were ruled out unsuitable for solar PV farms. Also, most alluvial plains, where suitable solar PV POAs are mostly found, were ruled unsuitable for wind farms when the 5.5 m/s wind speed threshold was applied.

However, if the land-use constraint is relaxed, there is a possibility for a co-located solar PV and wind farm in the municipalities of San Isidro and Catigbian (see buffered POAs in Fig. 9-b). These areas are comprised of 19 POAs, where 520 MW and 89 MW of co-located solar PV and wind farms can be constructed. The total annual energy which can be harnessed from these areas is approximately 797 GWh – more than enough to cover the 2030 demand of the province [37]. The conjoined BCR for these areas ranges from 2.1 to 2.2 when energy generated is paid under the hypothetical FiT Program and between 1.2 and 1.6 when the energy generated is paid below 5 Php/kWh– suggesting that these areas can only be viable when the project is subsidized. This is because wind speed in these POAs is very low (5.6–6.0 m/s), though the longest estimated spur line and access road are approximately 2 km and 3 km only. These POAs are also situated in agricultural lands where conversion to non-agricultural uses is difficult, if not impossible – a condition that may nullify this finding.

4.6. Compensation effect amongst variables and between technologies

Inherent to linear combination models, the compensation effect amongst variables is unavoidable. In Table 4, for instance, a wind farm can have a 10 km spur line and can still be considered a good

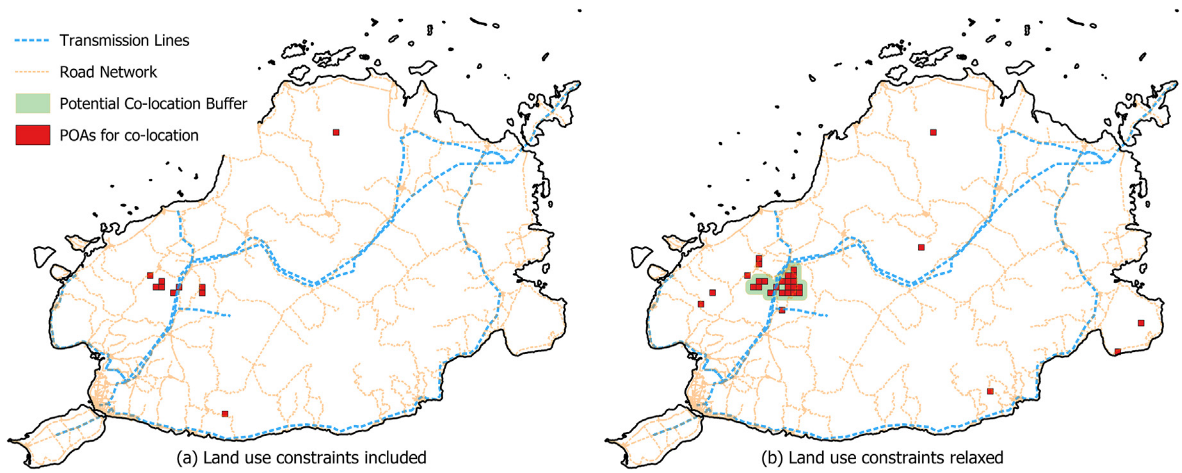

Fig. 9. Areas potential for solar PV and wind farm co-location.

investment choice at a BCR of 2. This is only possible because this POA (ID: 8323) is located near the road infrastructure, and it has a medium wind class at 7.8 m/s. It also appeared in Table 4 that a POA situated 5 km from the road network could also have BCR over 2 when the length of the spur line reduces to almost half the preceding condition. Moreover, POAs with very low wind speed can still have a BCR of 2 as long as the length of the spur line does not exceed 5 km and the length of the access road is less than a kilometre. This is the manifestation of compensation amongst variables. With this, it is important to point out that if we restricted the suitability of solar PV and wind to a certain distance such as 10 km from transmission line [7,8,41] or 5 km [28] from the road network, which is common in the GIS-MCDA approach, we could have also limited our insights.

Meanwhile, if we have not applied a threshold for wind speed, conjointly analyzing the viability of solar PV and wind technologies can allow areas with wind speed below 5 m/s to have a BCR of 2 (see Table 5). Owing to our assumption that a POA can be viable if BCR is greater than 1.5, it appeared that POAs with wind speed below 5 m/s can be regarded as a good investment. This modelling result is technically trivial and is the manifestation of the compensation effect between technologies. Similar to the compensation effect amongst variables, it is unavoidable. However, it can be managed by applying a wind speed threshold (see Table 5).

5. Sensitivity analysis

To investigate the effects of economic parameters on the viability of solar PV and wind farms in the study area and consider the uncertainties of the inputs, we performed sensitivity analysis by varying the interest rate, lifespan, CAPEX and fixed O&M cost of power plants, and CAPEX of power plants POI, spur line, and access road. Using the base scenario, we looked at how varying these parameters above and below base values will affect the total energy generation of the combined viable and highly viable POAs (at a BCR limit of 1.5). We used the percent rise/fall of energy generation as the variable because it directly links both the input and output of the model. While it depends on the project size and resource quality, the costs, benefits, and externalities rely on it. The results suggest that the model is very sensitive to interest rate, moderately sensitive to lifespan, slightly sensitive to CAPEX and fixed O&M of the power plant and CAPEX of the access road, and not sensitive to CAPEX of spur line and POI. As these parameters are weighing the spatio-technical inputs, their sensitivity (or non-sensitivity) is greatly influenced by our choice of base parameter values and the corresponding variations.

Table 5
The minimum wind speed vs BCR limit for PV/Wind case. Assumptions: land-use constraints included.

BCR Limit	Wind speed threshold applied				Wind speed threshold NOT applied			
	Scen1	Scen2	Scen3	Scen4	Scen1	Scen2	Scen3	Scen4
1.0	5.53	5.53	5.53	5.53	4.37	4.37	4.37	4.37
1.2	5.53	5.55	5.53	5.55	4.37	4.47	4.37	4.47
1.5	5.53	6.39	5.53	6.53	4.37	6.39	4.37	6.53
2.0	5.55	[a]	5.55	[a]	4.47	[a]	4.47	[a]
2.5	6.56	[a]	7.04	[a]	6.56	[a]	7.04	[a]
3.0	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]

[a] No POA has a BCR value more than the corresponding BCR limit.

6. Conclusions and future studies

Site selection for renewable energy technologies can be done in two approaches: (1) the GIS-MCDA approach and (2) the GIS-CBA approach. While the former became the most prevalent approach due to its simplicity and ability to incorporate intangible factors in the site selection process, the latter can be more intuitive and may produce less uncertain results. In this paper, we laid out the foundation of an emerging energy modelling framework based on CBA. A four-stage spatial cost-benefit-externality modelling framework that can assess the viability and estimate the externalities of VREs in a study area of any geographical scale was introduced. In this framework, the output is a viability map in which the degree of viability of VREs is measured using the benefit-cost ratio. Benefits and costs are estimated from developer's perspective, while externalities are separately calculated to assist planning and policymaking.

Using a scenario-based analysis, we implemented this framework to assess the viability and estimate the positive externalities of utility-scale grid-connected solar PV and wind farms in Bohol province. While considering the effects of selling price, land use constraints, and power density assumption, we analyze the viability of these technologies in three cases: solar PV, wind, and conjoined PV/wind. Our modelling results suggest that there is modest potential for viable and highly viable POAs in the study area. The selling price has a significant effect on the viability of POAs, and subsidizing the solar PV and wind projects in the study area appeared to be the compelling choice if the government wanted to see solar panels and wind turbines in the province's soil. Power density assumption can moderately affect the viability of VREs in the study area – suggesting the need for a future initiative aiming at establishing a database for actual power densities of installed solar PV and wind farms. Land use constraint limits the number of viable and highly viable wind projects in the study area, and relaxing this constraint can increase the possibility of unsubsidized wind farms. The likelihood that a co-located solar PV and farm is also difficult due to land use.

The compensation effect, inherent to linear combination models, is unavoidable and manifested in our results. Meanwhile, the model sensitivity to economic inputs was tested. It was found that the model is very sensitive to interest rate, moderately sensitive to plant lifespan, and slightly sensitive to CAPEX and fixed operation and maintenance costs of the power plant and CAPEX of the access road. However, it is not sensitive to the CAPEX of spur line and POI.

For future adoption of the model, additional externalities such as job creation in road construction and bulk transmission upgrade can be considered. Negative externalities such as displacement of agricultural activities can also be integrated into the model. It is also better to use a probabilistic approach for temporal parameters such as selling price. A less granular time scale such as monthly or daily can also be better to consider the temporal variability of solar and wind energy.

Data availability

Datasets related to this article can be found at https://doi.org/10.17632/c8x8pgpdz2.1, an open-source online data repository hosted at Mendeley Data [42].

CRediT authorship contribution statement

Dave J. Pojadas: Conceptualization, Methodology, Software, Writing – Original and Revised Draft Preparation, Visualization, Data curation, Formal analysis. **Michael Lochinvar S. Abundo:** Supervision, Conceptualization, Methodology, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2021.09.114.

Appendix B. Model symbols

Table B.1
List of symbols used in the model and their corresponding description

Symbol	Description
$\boldsymbol{BCR_j}$	The lifetime benefit-cost ratio of an energy generation project developed in a particular *j* POA considering *k* number of technologies, unitless
$\boldsymbol{l_j^{SL}}$	Estimated length of spur line needed to connect a particular *j* POA to the closest transmission infrastructure, km
$\boldsymbol{l_j^{rd}}$	Estimated length of access road needed to develop a given *j* POA, km
$\boldsymbol{A_{j,k}}$	Relative technology-to-POA coverage or the area of the suitable site of a particular *k* technology in a specific *j* POA, km^2
$\boldsymbol{q_{j,k}}$	Quality of wind speed or insolation in a given *j* POA, m/s or kWh/m^2
$\boldsymbol{NPV_j}$	Lifetime net present value of an energy generation project developed in a *j* POA considering *k* number of technologies, Php
$\boldsymbol{B_j^T}$	Total estimated lifetime benefits of developing a particular *j* POA into an energy generation project with *k* number of technologies, Php
$\boldsymbol{C_j^T}$	Total estimated lifetime costs of developing a particular *j* POA into an energy generation project with *k* number of technologies, Php
$\boldsymbol{AEG_{j,k}}$	The estimated annual energy that can be generated in a particular *j* POA when *k* number of technologies are developed in it, kWh
$\boldsymbol{P_{j,k}}$	The capacity of a particular *k* technology in a particular *j* POA, kW
$\boldsymbol{P_j}$	The total capacity of VRE projects in a particular *j* POA, kW
$\boldsymbol{CF_{j,k}}$	The capacity factor of a particular *k* technology in a particular *j* POA, unitless
$\mathrm{Tarr_k}$	The selling price of electricity generated by a particular *k* technology, Php/kWh
$\mathrm{I_{POI}^{cap}}$	The unit capital expenditures needed to build two substations, Php/kW
$\mathrm{I_{SL}^{cap}}$	The unit capital expenditures needed to construct transmission infrastructure, Php/kW-km
$\mathrm{I_{rd}^{cap}}$	The unit capital expenditures needed to construct an access road, Php/km
$\mathrm{I_{k}^{cap}}$	The unit capital expenditures needed to construct and install a power plant of *k* technology type, Php/kW
$\mathrm{I_{rd}^{OM}}$	The unit cost to maintain access road, Php/km
$\mathrm{I_{POI}^{OM}}$	The unit cost to operate and maintain two substations, Php/kW
$\mathrm{I_{SL}^{OM}}$	The unit cost to operate and maintain the spur line, Php/kW-km
$\mathrm{I_{k,n}^{fOM}}$	The annual fixed cost to operate and maintain the power plant considering *k* number of technologies, Php/kW
$\mathrm{I_{k,n}^{vOM}}$	The annual variable cost to operate and maintain the power plant considering *k* number of technologies, Php/kWh
μ	Availability factor of power plant

Table B.1 (*continued*)

Symbol	Description
j	POA index
k	Technology index
n	Year index

Note: Symbols in italics bold are the variables of the model. Symbols in normal texts are parameters of the model.

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