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Quantifying the Climate Co-Benefits of Hybrid Renewable Power Generation in Indonesia: A Multi-Regional and Technological Assessment

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Abstract: Quantifying the co-benefits of renewable energy investments can aid policymakers in identifying technologies capable of generating significant social, economic, and environmental benefits to effectively offset mitigation costs. Although there has been a growing body of work evaluating co-benefits, few studies have compared the potential co-benefits of several technologies across different regions in key countries. This study fills this gap by formulating a new modeling structure to assess the environmental–health–economic co-benefits of hybrid renewable energy systems (HRESs) in different parts of Indonesia. The proposed model is unique in that it incorporates various techno-economic activities to assess air quality, health, and economic benefits and then presents results as part of a cost–benefit analysis. From the intervention scenario, the modeling results show that installing 0.5 GW grid-connected solar PV, 100 MW of wind turbines, and a 100 MW biomass generator to cover a total of 1.64 million residential load units in the Bali province can avoid GHGs, $PM_{2.5}$, disability-adjusted life years (DALYs), and provide health savings of 1.73 Mt/y, 289.02 t/y, 1648, and 6.16 million USD/y, respectively. In addition, it shows that the payback period is enhanced by one year, while the net present value is increased by 28%. In Jakarta, a 3 GW solar PV plant and a 100 MW biomass generator that supply 5.8 million residential load units can deliver 32,490 averted DALYs and 652.81 million USD/y of health care savings. Nationally, the contribution of renewable energy to the electricity supply mix could grow from the 2020 baseline of 18.85% to 26.93%, reducing dependence on oil and coal contribution by 5.32%.

Keywords: climate policy; air quality; public health; energy transition; sustainable development

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1. Introduction

1.1. Background

In recent years, population growth, urbanization, and industrialization have led to a sharp increase in global energy demand [1]. This dramatic growth is clearly illustrated in the relevant data: global energy demand is projected to increase by 25% by 2040 [2]. Much of the increased demand will come from Asia; the region is currently the world's largest consumer of energy, and projections suggest it will stay that way for the foreseeable future [2]. In addition, developing countries in the region are likely to account for most of this growth. Many countries in Asia need energy to power their economies and deliver on a long list of development needs [3].

Although energy will be required to drive development across Asia, it is likely to give rise to other social and environmental concerns if it comes from fossil fuels. Fossil fuel combustion emits a wide range of health-damaging pollutants, including particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) [4]. Air pollution is attributable to seven million premature deaths annually across the world, most of which occur in low- and middle-income countries in Asia [5]. At the same time, fossil-fuel-based energy is the most significant contributor to Asia's fast-rising carbon dioxide (CO_2). These emissions contribute to warmer climates and many other adverse impacts (e.g., sea level rise, reduced crop yields, and disease outbreaks) that threaten to undermine sustainable development [6].

Fortunately, there is hope that countries in Asia can reverse the course on their reliance on fossil fuels [7]. Such a shift would involve adopting policies and programs that promote renewable energy, such as solar, wind, geothermal, biomass, and hydropower, as alternatives to fossil fuels. However, this kind of clean energy transition will not be easy. Some have rightly observed that relying on renewables is likely to generate questions about energy security, energy access, and economic growth [8]. It is also expected to raise concerns about costs that could potentially stall or weaken policies needed to boost investments and drive shifts in existing energy systems.

Transitioning to clean energy has significant potential in Indonesia. Indonesia is the world's fourth most populous country, and its energy demand has grown by 7% on average per year over the past decade [2]. Fossil fuels currently dominate the country's energy consumption, which is further illustrated by the fact that Indonesia is home to the seventh most coal-fired power plants globally [9]. At the same time, Indonesia's government has set a target to achieve 23% and 31% shares of renewable energy in the national electricity mix by 2025 and 2030 [10]. Furthermore, it has pledged to reduce 41% of greenhouse gas (GHG) emissions by 2030 in its nationally determined contribution (NDC) [10]. Yet, illustrating some of the tensions between clean and fossil fuels, renewables account for only 18% of the national energy mix at present. This is demonstrated in Figure 1 using data acquired from the International Energy Agency (IEA) [11].

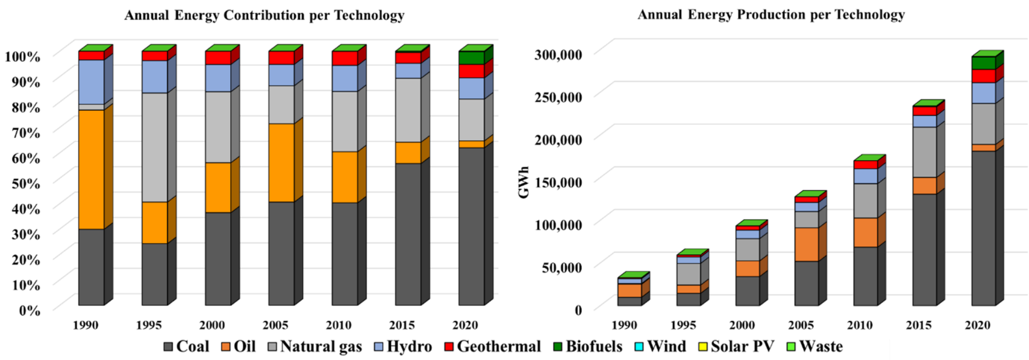

Figure 1. Indonesian historical electricity generation per production technology [11].

The challenges of the clean energy transition in Indonesia raise a critical question: what can decision makers do to trigger a shift toward renewables? A critical part of the answer involves co-benefits. Co-benefits are all the benefits arising from policies and programs that mitigate climate change while achieving other socioeconomic and environmental goals, such as improved air quality and better health. By quantifying and monetizing these additional benefits, it is possible to lower some of the cost-related concerns regarding clean energy transitions [12]. A clear and compelling demonstration of renewable energy co-benefits can bring together different stakeholders and build support for cleaner energy. This article primarily contributes by estimating the environmental and socioeconomic co-benefits of deploying diverse renewable energy technologies across various regions of Indonesia.

1.2. Literature Review

More than three decades ago, researchers studying the costs of mitigating climate change recognized that additional non-climate benefits could arise from investing in clean technologies [13]. These additional benefits (i.e., improvements in air quality and public health) merited attention because they reduce concerns about the investments in a climate problem that was widely viewed as long term and global. By estimating and illustrating what were initially called "ancillary benefits" and are now termed "co-benefits", policy makers could see near-term and local benefits from addressing global warming. These immediate and local benefits could help change the decision-making calculus on climate change [12]. They also opened opportunities to bring growing pools of climate finance to address air quality, health, and other development priorities.

Although the previous literature has analyzed the co-benefits obtained from climate policies based on air pollution or GHG separately [14], a growing number of contributions have focused on estimating the co-benefits by tackling climate change and air pollution simultaneously [15]. Several scholars have primarily measured two indirect co-benefits from climate policies: the avoided health loss and the monetary value of reducing air pollution [16]. Meanwhile, direct co-benefits refer to the air pollution reduction from climate policy [17]. This has produced two co-benefits modeling approaches.

First, constructing marginal abatement cost curves to estimate the monetary values of the co-benefits [18]. In this context, Nemet et al. have estimated that the average co-benefits of air quality from climate change mitigation in developing countries is 49 USD/tCO_2 [19]. However, this approach assumes a maximum abatement potential of the air pollutants, which constrains the resulting co-benefits of air pollution reduction [14]. The second approach estimates the avoided human loss from exposure to the enhanced air pollution level, resulting from adopting climate policy. For instance, Plachinski et al. have simulated plant-by-plant reduction in SO_2 and NO_x for various efficiencies, considering different renewable energy policies for carbon emission reduction in Wisconsin [20]. Furthermore, Permadi et al. have analyzed the co-benefits of emission-reduction measures of particulate matter and black carbon on premature mortality and climate radiative forcing in different regions of southeast Asia using a chemical transport modeling approach [21].

However, these approaches rely on the concentration of the ambient air pollutant rather than emissions, which can be modeled by using atmospheric or geophysical chemistry models such as GEOS-Chem [22]. Sequentially, Jiang has combined two models of measuring the pollution from end-of-pipe with climate strategies to quantify the air pollution co-benefits [23]. Alternatively, Bhat and Farzaneh have estimated the avoided human loss using the avoided emissions concentration by using the dispersion model and health risk assessment in multiple designated regions in India [24].

Another pertinent trend in the literature is using increasingly sophisticated models to quantify co-benefits for different technologies and sectors. To illustrate, studies have also looked at health-related co-benefits for interventions in the transport sector [25], as well as food and health-centered policies [26]. There has also been a growing focus on co-benefits across sectors and technologies in Asia, especially China. For instance, Zhao et al. have worked on the Chinese government's transportation, household, and industrial policies in the "2 + 26" regions using an integrated framework to reveal the reductions in average local concentrations of $PM_{2.5}$, PM_{10}, SO_2, and NO_2. This has been, respectively, translated into drops in premature deaths of 17%, 15%, and 45% for lung cancer, respiratory mortality, and cardiopulmonary cases, which have saved around 95.6 billion CNY [27]. Others have examined China's investments in Africa across different kinds of investment projects in hydropower, wind power, and solar PV [28]. Reyseliani and Purwanto have explored a 2050 pathway for Indonesia toward 100% renewable energy based on a least-cost optimization model that relies on an integrated market-reform system; they conclude that utility-scale solar PV could contribute up to 70% of national electricity production with one-sixth of the emissions of business-as-usual at a marginal abatement cost of 120 USD/CO_2 ton [29].

1.3. Research Gaps and Contributions

Although earlier contributions have offered increasingly robust estimates of the costs and benefits of varied interventions, there are still concerns that these contributions are not resonating with decision makers in key countries quickly enough to change the trajectory of development pathways [14]. Part of the reason for these concerns is a disconnect between the evidence of co-benefits and their incorporation in policy decisions, which may be because current modelling frameworks do not allow for comparisons of costs and benefits between different kinds of technologies across different parts of the country. This study aims to strengthen the connection between evidence and policy by addressing these gaps. It will further aim to do so in Indonesia, a country that—with few exceptions [29]—has seen relatively little research on co-benefits.

This study formulates a new interactive modeling structure to quantify the potential co-benefits of hybrid renewable energy systems (HRESs) for various locations in Indonesia. The proposed approach explores the potential for solar, wind, and biomass energy production technologies by assessing the desired supply and demand capacities for grid-connected or off-grid microgrids. Potential co-benefits are quantified based on their economic feasibility, environmental indices, and social and public health impacts. The model is unique in that it considers the endogenous parameters for various climate policies by allowing for investigation of the impact of energy production technology based on different energy-oriented technical assessments (i.e., feedstock types, solar PV array types, etc.) as well as varying site-specific variables (i.e., population, gross regional product per capita, etc.).

The main contributions of the study are threefold, as follows:

- Formulating an interactive modeling structure to quantify the environmental–health–economic co-benefits of implementing HRESs.
- Assessing the co-benefits obtained from HRESs based on various locations, technologies, and policies.
- Evaluating the Indonesian stated policies scenario of 2025 and 2030, considering the co-benefits from HRESs.

2. Methodological Approach

This study develops a methodological approach that quantifies the environmental–health–economic co-benefits of hybridizing solar, wind, and biomass electricity production technologies in Indonesia. The proposed approach consists of four main steps: (1) scenario definition and system configuration, where the HRESs electricity production technologies and electricity demand are sized and allocated; (2) data acquisition that involves collecting local, technical, emissions, health, and economic data; (3) calculation of the activity parameters, which include the energy balance equation of electricity generation and consumption of the HRESs resources; and (4) assessing and quantifying the environmental–health–economic co-benefits as a result of replacing conventional methods with the cleaner HRESs electricity.

2.1. System Configuration and Scenario Definition

Two main configurations are considered based on the standard definition of hybrid renewable microgrids. The off-grid configuration deals with the HRES that is not connected to the utility grid, and the reliability of the electricity generation is ensured by using an energy storage system like a battery bank [30]. On the other hand, the grid-tied configuration allows for the HRES to be connected to the electricity grid and sell back surplus electricity, using a feed-in-tariff scheme [31].

The scenarios can be defined by sizing and hybridizing the solar photovoltaics, wind turbines, biomass energy generators, and battery banks with respect to the load type and size, as shown in Figure 2. Biomass generators and battery banks in this study cover the base load and renewable energy intermittency in the grid-tied and off-grid configurations, respectively. Therefore, the simultaneous operation of battery storage and biomass generator systems is impermissible, which means that when a grid-tied scenario is considered, the grid replaces the battery bank, and the possibility of power exchange with the grid is evaluated.

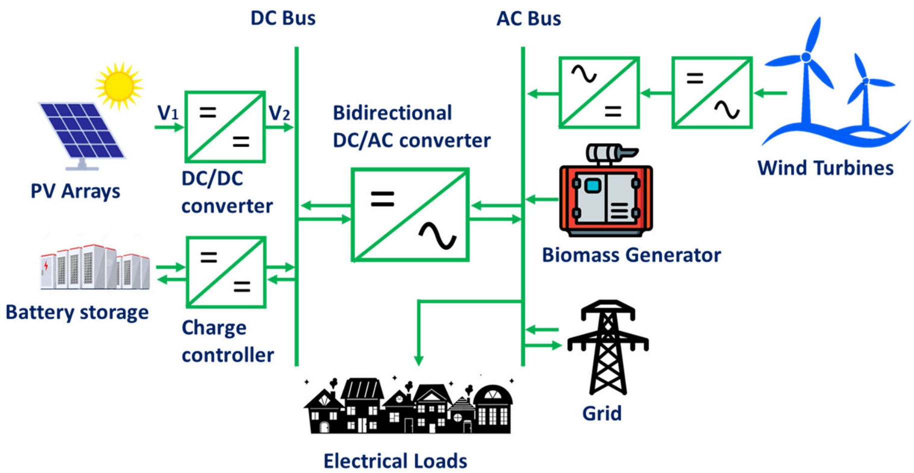

Figure 2. HRESs configurations.

2.2. Data Acquisition

The acquired local data include geographical and meteorological data from selected locations in Indonesia. The study covered 112 measurement fields from all the provinces of Indonesia. The geographical field information was organized by region, city, latitude, longitude, time zone, and elevation. The meteorological hourly datasets comprised dry bulb temperature (°C), relative humidity (%), global horizontal radiation Wh/m^2, direct normal radiation Wh/m^2, diffuse horizontal radiation Wh/m^2, and wind speed (m/s). The data were collected regarding typical meteorological years (TMY) [32]. The TMY climate files were derived from the US NOAA's Integrated Surface Database (ISD), which was processed using the TMY/ISO 15927-4:2005 methodologies. The datasets selected for the targeted cities were based on the most recent 15 years, from 2007 to 2021.

On the other hand, data on gross regional product per capita (GRP) for Indonesian provinces and the population number per province were collected from Badan Pusat Statistik [33]. The $PM_{2.5}$ exposure indices were obtained from the Energy Policy Institute of the University of Chicago [34]. The capital expenditures and operating expenses of the HRESs in Indonesia were gathered from the Japan International Cooperation Agency [35], while the electricity tariff of exchanging the electricity with the grid was 0.0925 USD/kWh, as collected from the International Energy Agency [36]. The emission factors of the power grid per pollutant were acquired from the U.S. Environmental Protection Agency [37], as provided in Table S6 in the Supplementary Materials (See Section S8). The supply and demand technical specification data of the electricity generation resources are explained in the Supplementary Materials (Sections S1–S5) and provided in the tables of Section S8.

2.3. Calculation of the Activity Parameters

The hourly electricity generated by the proposed HRES is the main activity parameter. Based on defining the configuration and scenario, the HRES aims to prioritize supplying the loads with clean energy, then selling the surplus electricity to the grid or charging the batteries to maximize profits. Supplying loads with grid power has the lowest priority only when the HRES does not meet the set demand. The overall energy balance equation is formulated based on the given system's configuration. Equation (1) shows the overall system's energy balance for all the resources.

$$E_{PV t} + E_{WT t} + E_{BG t} + E_{Grid\_Pur t} + E_{BD t} = E_{Load t} + E_{BC t} + E_{Grid\_Sell t} \quad (1)$$

where $E_{PV t}$ is the hourly generated electricity from solar panels. $E_{WT t}$ is the hourly generated electricity from wind turbines. $E_{BG t}$ is the hourly electricity generated from the biomass generator. $E_{Grid\_Pur t}$ is the hourly purchased electricity from the grid. $E_{Grid\_Sell t}$ is the hourly sold electricity to the grid. $E_{BD t}$ is the hourly discharged electricity from batteries. $E_{BC t}$ is the hourly charged electricity to the battery. $E_{Load t}$ is the hourly electricity demand that should be met at the time step of t. t is the time step in hours. The overall modeling flowchart of the activity parameters is depicted in Figure 3, while the detailed calculation methodologies are explained in the Supplementary Materials (See Sections S1–S5).

2.4. Potential Reduction in GHG Emissions and Air Pollutants

The viability of the avoided emissions stems from estimating the substitution of the polluted electric energy of the national grid with cleaner HRES electricity. This is mathematically expressed using Equations (2)–(4).

$$AE = (E_T - E_c) \times EF_{p,grid} \quad (2)$$

$$E_T = \sum_t \sum_\tau E_{\tau,t} \quad (3)$$

$$E_c = \sum_t \sum_\tau C_{\tau,t} \quad (4)$$

where AE is the annual avoided GHG emissions and air pollutants in tons per year. E_T and E_c are the annual total electricity generation and the annual self-electricity consumption of the proposed HRES per year, respectively. $EF_{p,grid}$ is the electricity grid's pollutant emission factors. $E_{\tau,t}$ is the hourly electricity generation per the technology τ(i.e., solar, wind, biomass, and battery). $C_{\tau,t}$ is the hourly self-electricity consumption of technology τ.

2.5. Public Health Co-Benefit Assessment

The proposed methodology in this research uses disability-adjusted life years (DALYs) to indicate the mortality caused by the different diseases. DALYs are defined as the total of years of potential life lost from premature death and disability-related diseases. The percentage change in the health outcome for each unit change in $PM_{2.5}$ concentration is used to calculate the effect estimates for DALYs.

The health burden of the population was obtained based on selected diseases for the exposure group in the targeted locus of Indonesia. The diseases encompass chronic obstructive pulmonary disease (COD), ischemic heart disease (IHD), cerebrovascular disease (Stroke), lung cancer (LC), tuberculosis and bronchus (TB), and acute lower respiratory infections (ALRI). The relative risk of the exposure level of interest for the subject diseases is a function of the health response to a change in $PM_{2.5}$ concentration per pollutant concentration, and the pollutant concentrations change with respect to the baseline indices, as expressed in Equation (5).

$$RR_{m,n} = \mathrm{f}(\beta, \Delta C_{PM}) \quad (5)$$

where $RR_{m,n}$ is the relative risk of the exposure level of interest for the subject diseases. β is the coefficient of the health response to a change in $PM_{2.5}$ concentration. ΔC_{PM} is the pollutant concentrations change with respect to the baseline indices. In this study, a dispersion model is developed to find the pollutant concentrations change considering the baseline concentration of $PM_{2.5}$ as the major air pollutant. This is explained in Section S6 in the Supplementary Materials. m and n are the selected disease and the exposure group, respectively.

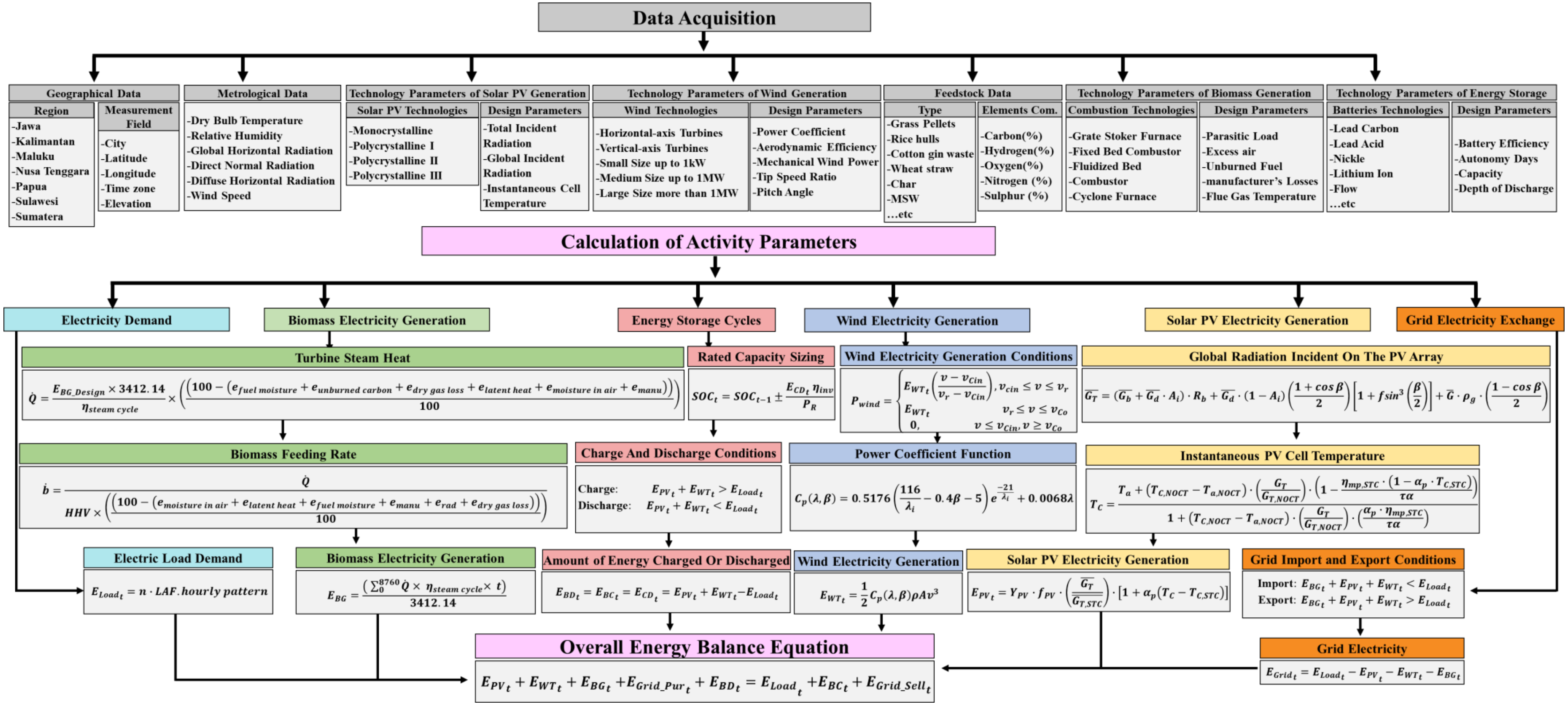

Figure 3. Calculation flowchart.

Sequentially, based on the obtained relative risk, the population-attributable risk fraction ($PAF_{m,n}$) for the selected disease was calculated using Equation (6) [38].

$$PAF_{m,n} = \frac{RR_{m,n} - 1}{RR_{m,n}} \tag{6}$$

The overall mortality and morbidity are measured using the following equations [39]:

$$ADALYs_{m,n} = \left(DALYs_{m,n,base} \times PAF_{m,n,base}\right) - \left(DALYs_{m,n,int} \times PAF_{m,n,int}\right) \tag{7}$$

where $DALYs_{m,n}$ is the DALYs attributable to the selected disease (m) in the exposure group (n), which are given in Table S1 in the Supplementary Materials (See Section S8). $ADALYs_{m,n}$ is the DALYs averted from the intervention scenario, after deploying the proposed HRES. *base* and *int* denote baseline and intervention scenarios. The values of the $DALYs_{m,n,base}$ for the selected diseases are given in Table S1 in the Supplementary Materials as obtained from [40] (See Section S8).

The monetized benefits of averted DALYs can be estimated based on the per capita gross domestic product (PGDP) that an individual with a healthy life can achieve in one year [39]:

$$AVC_{n,m} = PGDP \times ADALYs_{m,n} \tag{8}$$

where $AVC_{n,m}$ represents the avoided cost of mortality and morbidity due to averted DALYs in a year.

2.6. Cost–Benefit Assessment

The profitability of the intervention scenario was investigated through the economic feasibility of implementing the HRES resources. This includes the net profit values, payback period, and marginal abatement cost. In this study, the amount of energy imported from the national grid to balance the unmet demand of HRES was considered purchasing expense, while the surplus energy exported to the national grid was considered revenue. Given this, the cost–benefit analysis of integrating the HRES can be exploited as expressed in Equations (9)–(13):

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} - C \tag{9}$$

$$R_t = (AS_t - CE_t) \tag{10}$$

$$AS_t = AS_{Elctricity,t} + AS_{Co-benefits,t} \tag{11}$$

where NPV is the net present value calculated for the period of the project lifetime. R_t represents the cash flow at year t, which is calculated by subtracting the outflow cash from the inflow cash. C is the total capital and installation costs. T is the project lifetime, and r is the discount rate. AS_t is the incoming cash flow, which includes the revenues of selling electricity to the HRES's end customers and the national grid as denoted by $AS_{Elctricity,t}$. In addition, the monetized health co-benefits (AVC) as obtained in the previous section are included in the incoming cash flow calculation, which is denoted by $AS_{Co-benefits,t}$. CE_t is the outflow cash, including fixed, operational, and maintenance costs. Sequentially, the payback period of the utilized HRES was calculated annually considering the total capital and installation costs, and the marginal annual cash flow is shown in Equation (9) and Equation (12), respectively [41]. The marginal abatement cost of the total GHG emissions abated over the project lifetime was calculated as expressed in Equation (13) [42].

$$PBP = \sum_{t=1}^{T} \frac{C}{\frac{R_t}{(1+r)^t}} \tag{12}$$

$$MAC = \frac{-NPV}{TEA} \tag{13}$$

where PBP is the payback period calculated per annum. MAC is the marginal abatement cost in USD per ton of GHG emissions abated. TEA is the cumulative GHG emissions abated over the project lifetime in tons.

3. Results and Discussion

In this section, the study aims to demonstrate the effectiveness of the proposed modeling structure in highlighting the quantified environmental–health–economic co-benefits through three streams. First, technology-wise impact assessment is oriented toward varying the technologies, configurations, and sizes of the supply resources to assess the quantified co-benefits within the same region. Second, regional-wise impact assessment is oriented toward varying the regions considering the same technologies, configurations, and sizes of the supply resources. Third, the economically viable scenarios from the first two streams will be consolidated to assess the Indonesian stated policies scenario. In the first two streams, the technologies, configurations, and sizes of the supply resources are selected to meet the Indonesian stated policies scenario, as detailed in Section 3.3.

3.1. Technology-Wise Impact Assessment

The technology-wise impact assessment was structured to pinpoint the impact of the broad technical range on the integrated environmental–health–economic co-benefits. The estimated co-benefits are demonstrated and discussed in the following subsections based on various selections of HRES's activity parameters in Bali and Jakarta.

3.1.1. The Case of Bali

Figure 4 shows four different scenarios (i.e., S1, S2, S3, and S4) that vary based on system configuration and generation technologies in the province of Bali. S1 is an off-grid microgrid that relies on a 100 kW installed capacity of solar PV, two wind turbines, each with a capacity of 1 MW, 8 MWh battery storage systems, and 2400 residential load units. S2 is similar to S1 with a difference in grid-connected configuration and excluding the battery storage from the system. S3 is a 0.5 GW grid-connected solar PV, 100 MW installed capacity of wind turbines, and 1.04 million residential load units. S4 is similar to S3 by installing a 100 MW biomass generator and a total of 1.64 million residential load units. The residential load units' number was determined based on the per capita consumption in Indonesia, as explained in Section S1 of the Supplementary Materials. The technical specifications of the implemented HRES are provided in Section S8 in the Supplementary Materials.

The major input and output parameters of the three scenarios are consolidated in Tables 1 and 2, respectively. It was observed that S1 is not economically viable in the project's lifetime due to the high capital costs invested in the energy storage systems. However, the long-term energy storage economic viability of the energy storage system can be further assessed by considering different scales and carbon prices in future directions. In comparison to S1, S2 is economically viable, yet the obtained co-benefits are low due to the low-scale installed capacities. S3 is a profitable scenario due to the higher amount of renewable energy supply that can be traded with the national grid. In addition, the avoided GHG, $PM_{2.5}$, DALYs, and delivered health savings show remarkable indices, which are consequences of replacing the polluted grid's electricity with clean HRES sources. Last, the impact of adding 100 MW of biomass generation in S4 has shown better performance in the avoided GHG, $PM_{2.5}$, DALYs, and improved health savings by around 30% compared to S3, whereas it is reflected in the payback period improvement and annual cash flow. Furthermore, considering the integrated environmental–health–economic co-benefits, the projects' NPVs of S3 and S4 have enhanced by 13.1% and 28.08%, respectively. However, although the integrated environmental–health–economic co-benefits show remarkable indices, the slight enhancement in the cost–benefits analysis when considering the co-benefits can be justified by the low $PM_{2.5}$ exposure index of 10.62 $\mu g/m^3$ in the Bali province.

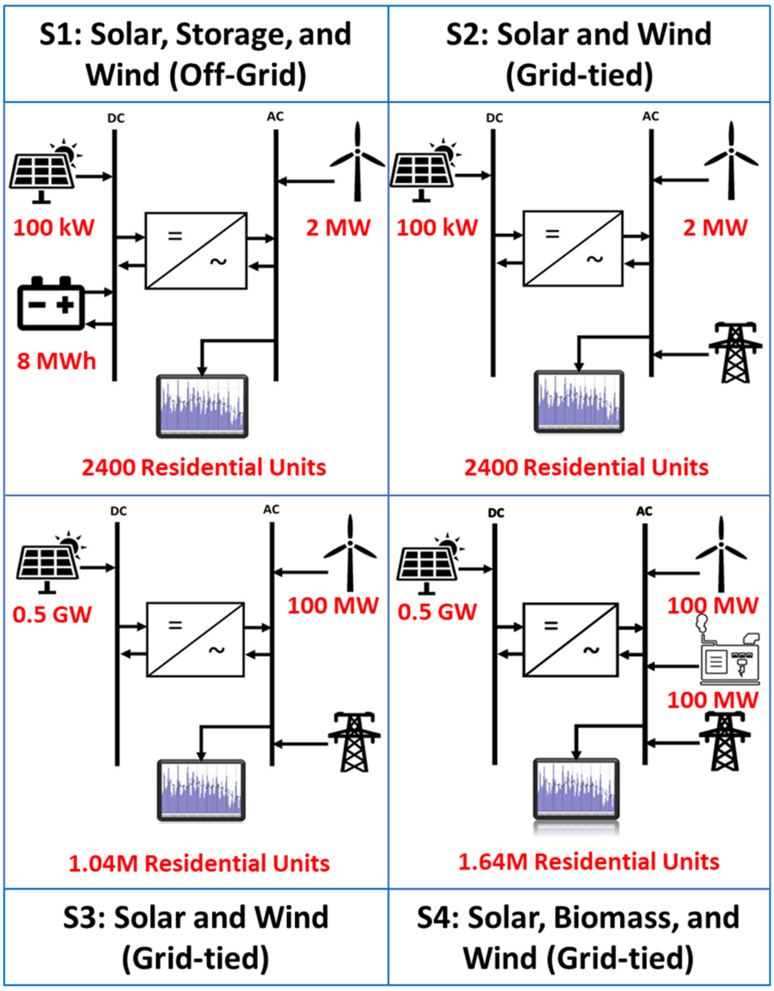

Figure 4. Scenario definitions based on system configurations and production technologies of the first four scenarios.

Table 1. The input parameters for the co-benefits analysis of the different scenarios.

Scenario		**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
Assessment		------------------------------**Technology-Wise**-----------------------						**--Region-Wise--**	
Province		**Bali**	**Bali**	**Bali**	**Bali**	**Jakarta**	**Jakarta**	**Aceh**	**East Java**
Residential Load Unit Number		2400	2400	1.04M	1.64M	5.80M	5.42M	7.28M	7.33M
Demand	(GWh)	2.6	2.6	1117	1762	6239	5830	7827	7891
HRES Supply	(GWh)	2.6	2.6	1122	1769	6266	5851	7858	7923
Grid Supply Sell	(GWh)	0	1.17	517	546	2945	2720	4320	4310
Grid Supply Purchase	(GWh)	0	1.17	512	539	2918	2699	4289	4278
Energy Storage Capacity	(MWh)	8	-	-	-	-	-	-	-
Solar Installed Capacity	(MW)	0.1	0.1	500	500	3000	3000	4000	4000
Wind Installed Capacity	(MW)	2	2	100	100	-	-	-	-
Biomass Installed Capacity	(MW)	-	-	-	100	100	100	-	-

Table 2. Results of co-benefits analysis of the different scenarios.

Scenario			**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
Avoided GHG		(Mt/y)	0.0025	0.0025	1.1	1.73	6.14	5.73	7.7	7.76
Avoided $PM_{2.5}$		(t/y)	0.45	0.45	199.68	289.02	1088.01	1014.11	1398.76	1410.24
Averted DALYs			3	3	1136	1648	32,490	30,146	11,818	116,835
Health Savings		(M USD/y)	0.9	0.9	4.25	6.16	652.81	605.72	31.16	522.14
NPV	Without Co-benefits	(M USD)	−143.39	−67.93	−8495.58	−5747.00	−35,385.42	−54,414.46	−32,086.23	−30,770.96
	With Co-benefits	(M USD)	−140.847	−65.45	−7384.78	−4135.53	135,265.88	103,926.07	−23,939.66	105,720.31
PBP	Without Co-benefits	(Yrs)	>25	>25	18	15	17	20	15	15
	With Co-benefits	(Yrs)	>25	>25	17	15	7	8	15	9
Marginal Abatement Cost	Without Co-benefits	(USD/t)	1890.41	917.21	257.76	110.56	192.21	316.54	138.98	132.19
	With Co-benefits	(USD/t)	1856.88	883.68	224.06	79.56	−734.74	−604.56	103.69	−454.18

3.1.2. The Case of Jakarta

Another scenario, S5, was investigated to scrutinize the potential co-benefits of a large-scale solar PV plant and biomass generator in the capital city Jakarta, where the highest $PM_{2.5}$ exposure index of 32.08 µg/m^3 is present. The assessment was conducted by utilizing a 3 GW solar PV plant equipped with monocrystalline modules and a 100 MW fluidized bed combustor biomass generator operated with feedstock of char from wheat straw II. The system was grid-tied and configured with a planned demand consisting of 5.80 million residential load units, as demonstrated in Figure 5.

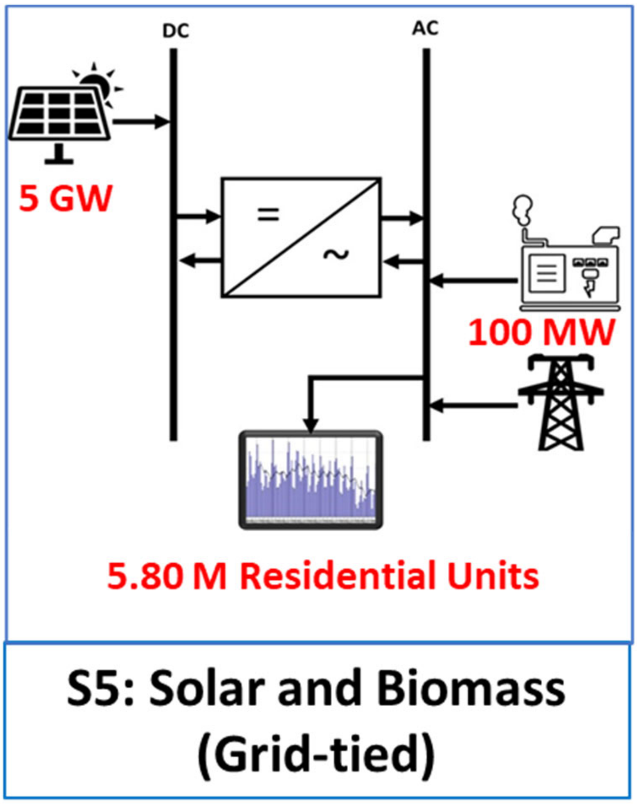

Figure 5. Configuration and production technologies of scenario S5.

Based on the avoided emissions indices, the project's breakeven can be recovered in 17 years without considering co-benefits and in 7 years considering the co-benefits. As a result, the project has higher NPV and lower marginal abatement cost considering co-benefits, as shown in Table 2. The substantial enhancement of the cost–benefit analysis stems from the highest population density and $PM_{2.5}$ index among Indonesian provinces of the capital city, Jakarta. The health and economic co-benefits depicted in Figure 6 include 32,490 averted DALYs and 652.8 million USD/y of healthcare savings, as shown in Table 2.

To investigate the technical specification impact of the selected monocrystalline solar PV modules on the obtained co-benefits, similar given parameters of the 3 GW large-scale solar PV plant and biomass generator in S5 have been implemented using polycrystalline solar PV modules to form S6. Consequently, the annual produced RE supply was degraded by 6.62%, affecting the integrated environmental–health–economic co-benefits and cost–benefit assessment, as shown in Tables 1 and 2, respectively.

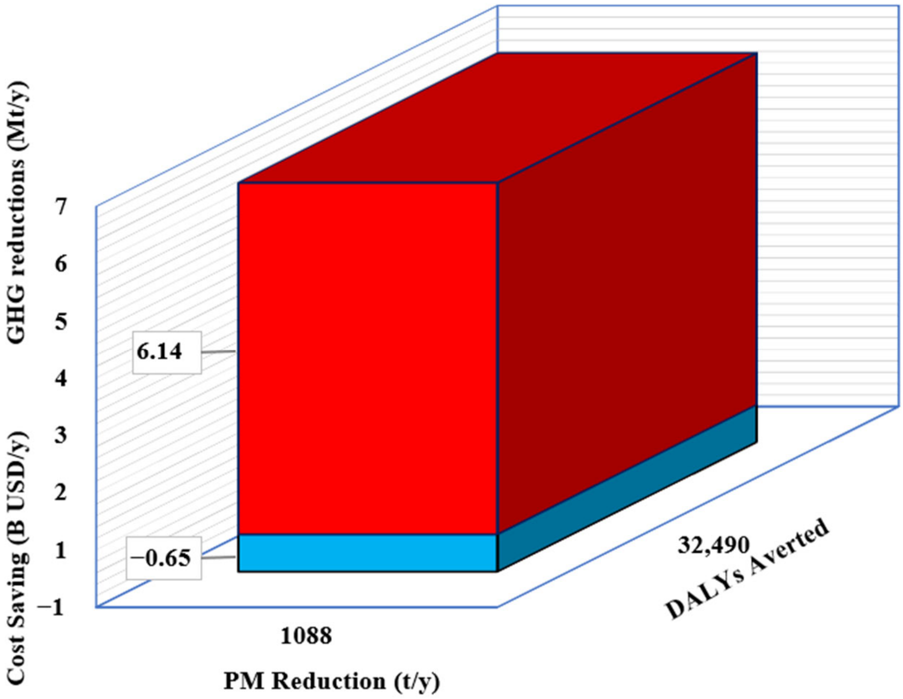

Figure 6. Integrated environmental–health–economic co-benefits scenario S5.

3.2. Regional-Wise Impact Assessment

The regional impact assessment was explored based on two criteria. Firstly, finding the best location to harvest solar and wind energy is the main activity parameter to obtain the integrated environmental–health–economic co-benefits. In this context, the developed model was employed to estimate the annual electricity production from the 1 kW installed capacity of solar PV and wind turbines throughout the covered 112 measurement fields from all the provinces of Indonesia. Figure 7 demonstrates the study's covered locations and the potential of the annual solar PV and wind production. It is observed that, although the solar PV output potential is high in all provinces, wind electricity can be harvested efficiently in specific locations.

Secondly, the integrated environmental–health–economic co-benefits were investigated based on the implementation locations, including the GRP, population density, $PM_{2.5}$ exposure index, and climate parameters. In this context, the study applied new intervention scenarios of S7 and S8, where the technical specifications of both scenarios were similar. Both scenarios were grid-tied and configured with a solar PV installed capacity of 4 GW. However, it varied based on the implementation locations, which have different GRP, population density, $PM_{2.5}$ exposure index, and climate parameters. East Java is the province of S8 with a population number, GRP, and $PM_{2.5}$ exposure index of 37.48 million, 4469 USD, and 17.93 $\mu g/m^3$, respectively. Meanwhile, in Aceh, the province of S7, the population number, GRP, and $PM_{2.5}$ exposure index are 4.49 million, 2637 USD, and 14.30 $\mu g/m^3$, respectively. This demonstrates that all the locational indices are higher in East Java. The number of residential units was determined based on the per capita consumption in Indonesia, as explained in Section S1 of the Supplementary Materials.

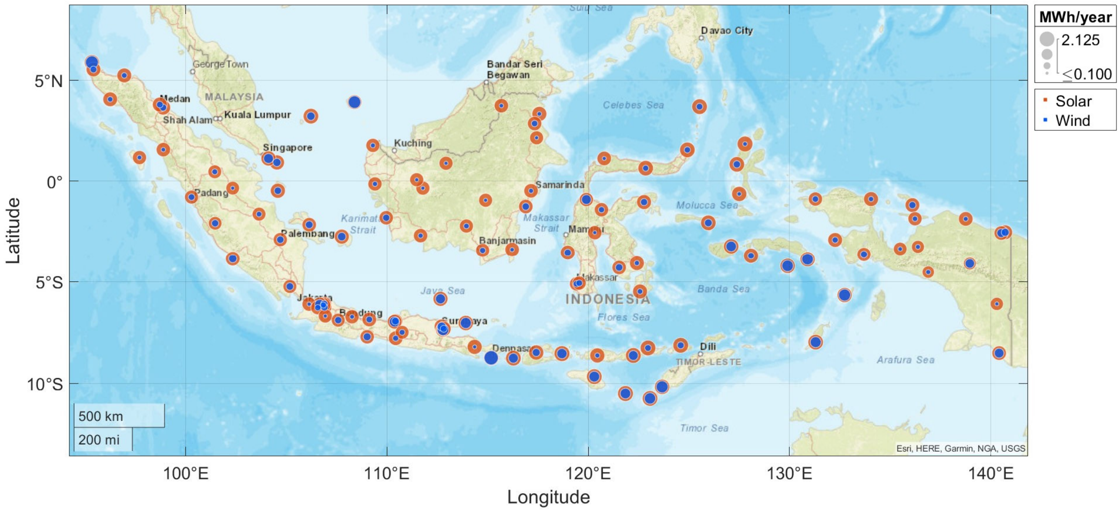

Figure 7. Annual production of variable renewable energy per 1 kW installed capacity.

The higher population density, GRP, and $PM_{2.5}$ exposure indices are expected to drive S8 to higher co-benefits achievements, as demonstrated in Figure 8, which compares all the intervention scenarios. In addition, Tables 1 and 2 show the input and output comparison indices of S7 and S8, considering the 4 GW installed solar PV plant, respectively. The slightly higher supply of renewable energy in S8 stems from the better solar irradiation potential in East Java, while this supply difference can justify the slightly higher reduction in GHG and the cost–benefits analysis without considering the co-benefits in S8. However, considering the co-benefits, the remarkable indices between the two scenarios in Table 2 directly reflect the higher population density, GRP, and $PM_{2.5}$ exposure index in East Java, as reported in Table S7 in the Supplementary Materials (See Section S8). Furthermore, this can be measured using the ratio of the averted DALYs to the annual generated electricity from HRES, which is the 4 GW installed solar PV plant. The ratios for S7 and S8 are 1.54 and 14.75, which means that due to the higher population density, GRP, and $PM_{2.5}$ exposure index in East Java, a one annual gigawatt-hour can attain an averted DALYs of 14.75. These ratios can be compared with the 0.80 reported by the authors in an earlier contribution for Ulaanbaatar city in Mongolia [39]. However, it is worth noting that the solar irradiance potential, baseline mortality function for different diseases, population density, GRP, and $PM_{2.5}$ exposure index vary across the regions.

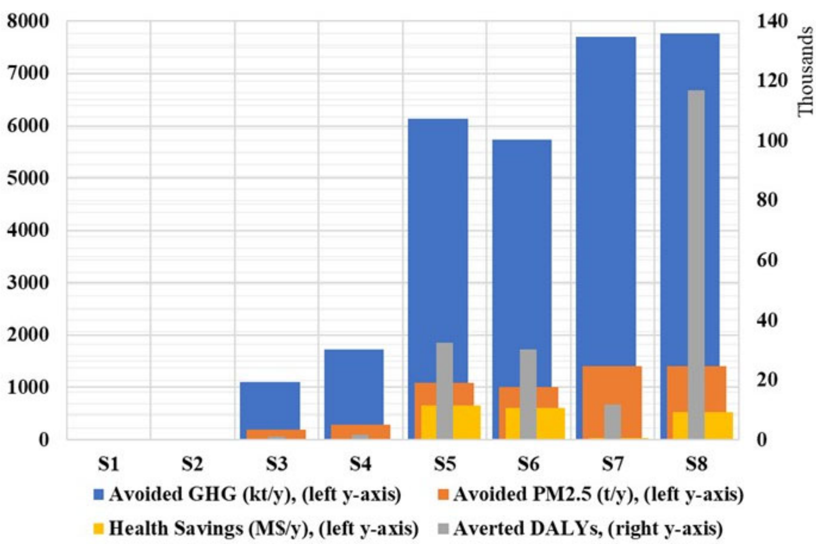

Figure 8. Comparison of the co-benefits analyses of the different scenarios.

3.3. Stated Policies Scenarios Assessment

The stated policies scenario (STEPS) is a sector-by-sector assessment to tackle climate change, whereby Indonesia is committed to the sustainable development scenario of the Paris Agreement to limit the temperature below two degrees Celsius. This includes increasing the contribution of renewable energy to the national supply energy mix to 23% and 31% by 2025 and 2030, respectively, and reducing 41% of greenhouse gas (GHG) emissions by 2030 [10]. The Indonesian baseline data of 2020 were collected from IEA's data explorer [11], and include the contribution of energy production per technology and historical carbon emissions per sector, as depicted in Figures 9 and 10, respectively.

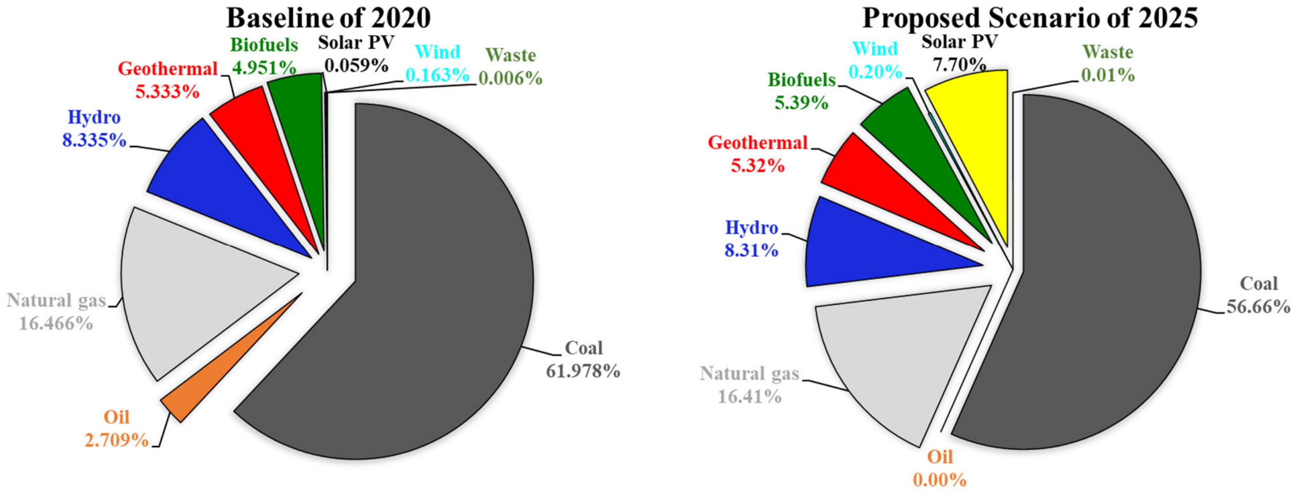

Figure 9. Contribution of energy production per technology to the national supply mix before and after the proposed scenario [11].

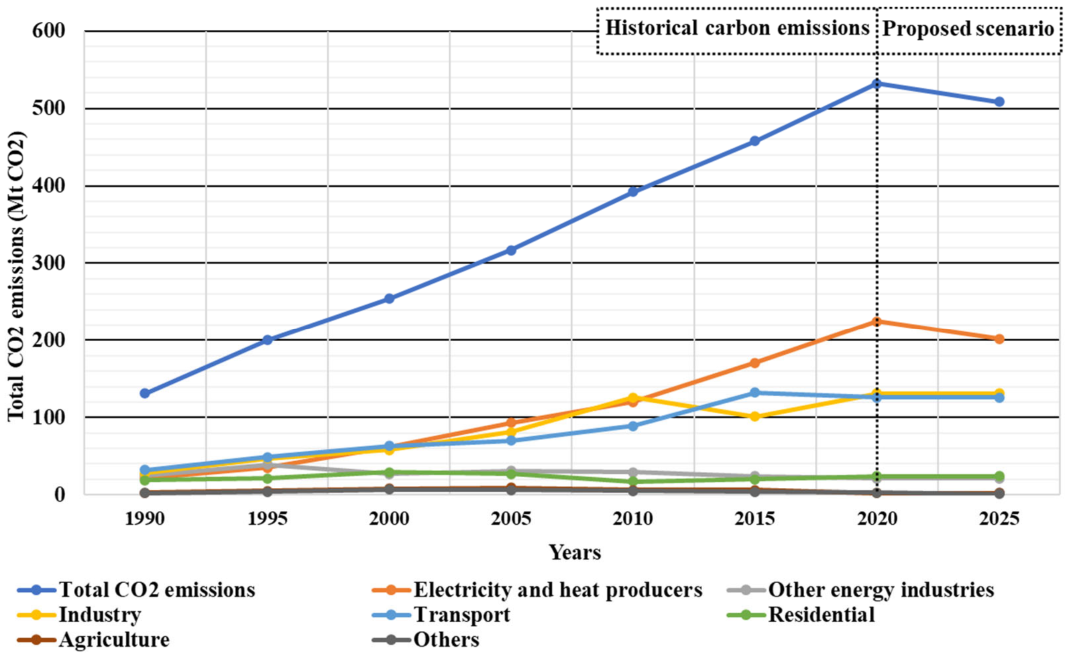

Figure 10. Historical carbon emissions per sector and after the proposed scenario [11].

This study employed the developed methodology to assess the integrated environmental–health–economic co-benefits associated with the committed STEPS. To this aim, the feasible intervention scenarios of S4, S5, S7, and S8 were consolidated in one scenario, reflecting the STEPS, and compared with the baseline data of 2020 to find the associated co-benefits. The total installed capacity of solar PV, wind turbines, and biomass generation in various provinces throughout the country are 11.5 GW, 0.1 GW, and 0.2 GW, respectively. This generates an annual renewable energy production of 23.78 TWh, which supplies a total demand of 24.63 TWh. The proposed installation capacities of the HRES and the demand of this scenario align with the projected demand escalation of 2025 and the solar plus scenarios presented by the IEA [36]. However, the report attempted to evaluate the STEPS commitments from the perspective of tackling short-term power system challenges, focusing on transmission and distribution infrastructure. In this study, the proposed installation capacities of the HRES tend to highlight the quantifications of the attainable co-benefits. Figure 11 shows the integrated environmental–health–economic co-benefits of the STEPS based on the conducted technological and regional impact assessments. On the other hand, the NPV with co-benefits is the primary metric used to detect the attained co-benefits. This has been plotted in Figure 12 versus the major affecting parameters of discount rate, solar installed capacity, and electricity tariff. The multiplication ratio shows the percentage change in the affecting parameters, whereas 1 indicates the default parameters applied in the STEPS scenario. The applied discount rate is 6.46%, solar installed capacity is 11.5 GW, and the electricity tariff is 0.0925 USD/kWh. It is observed that the electricity tariff is the parameter that enhances NPV the most, followed by the discount rate, and solar installed capacity, sequentially.

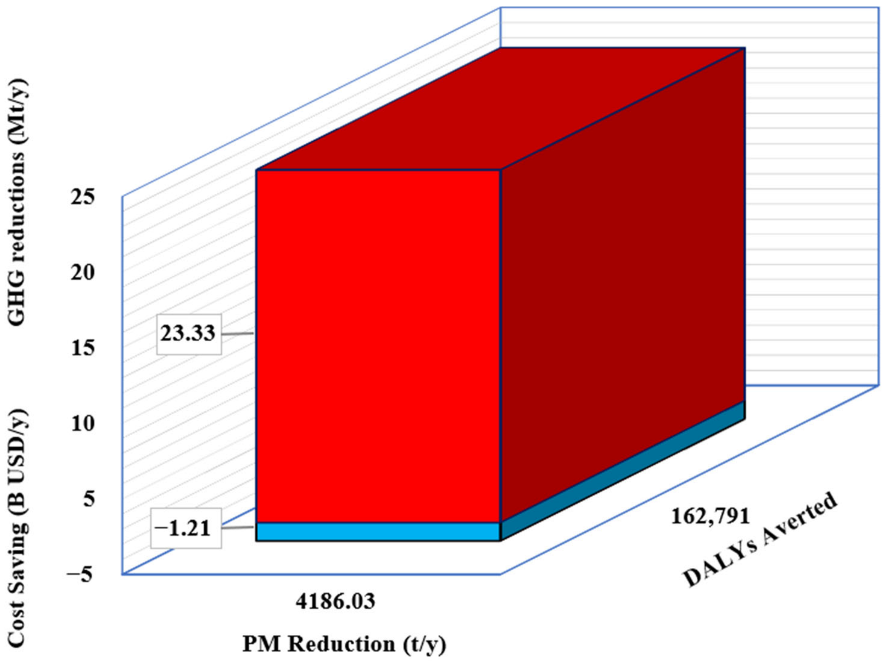

Figure 11. Integrated environmental–health–economic co-benefits of the STEPS in Indonesia.

Figure 9 demonstrates the contribution of each energy production technology to the national supply mix in at baseline of 2020 versus in the scenario proposed by this study to meet the STEPS. It is observed that the total contribution of renewable energy, including hydroelectric power, to the national supply energy mix in 2020 was 18.85%, while in the STEPS it is 26.93%. On the other hand, the increased penetration of renewable energy sources has knocked out oil and decreased the coal contribution by 5.32%.

Sequentially, Figure 10 shows the country-wise historical carbon emissions per sector before and after the study's proposed scenario to meet the STEPS, where the avoided GHG of 23.33 Mt/y is reflected in the electricity sector emissions and the total country emissions, respectively. This forms a total of 4.4% of the total emissions, constituting 10.73% of the committed STEPS for 2030.

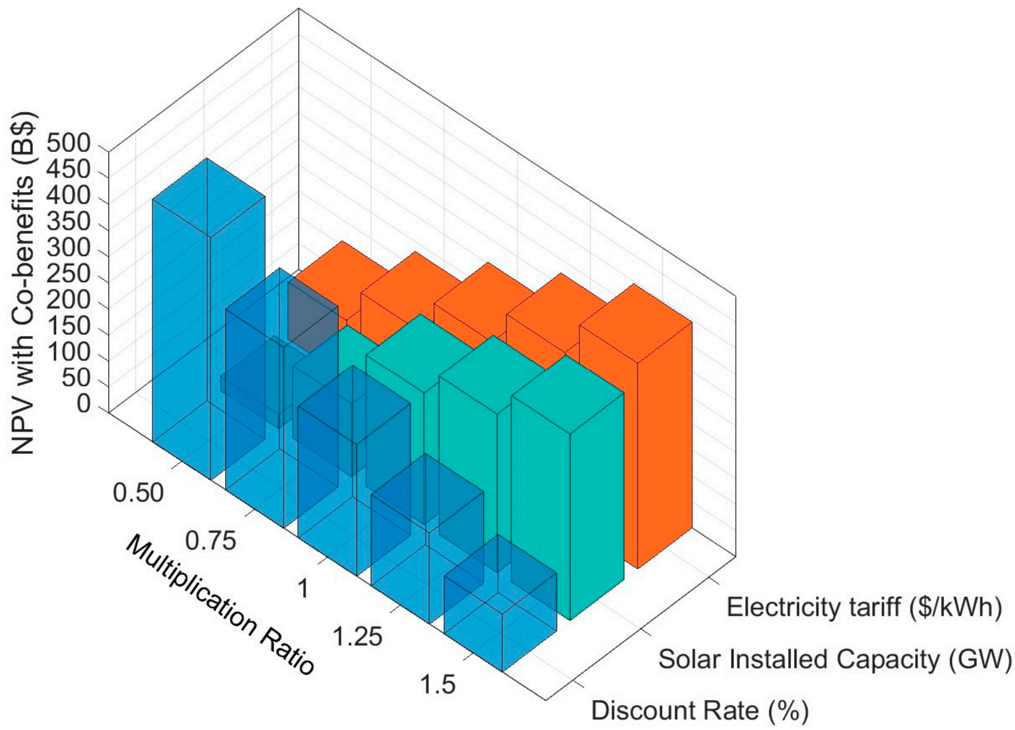

Figure 12. Sensitivity analysis of the major affecting parameters versus the NPV with co-benefits.

In compliance with the STEPS, the integrated co-benefits of the avoided GHG emissions for the selected scenarios encompass 4186 t/y avoided $PM_{2.5}$, 162,791 averted DALYs, and health savings of 1.21 B USD/y. The total NPV of the selected scenarios considering the integrated co-benefits is enhanced to 213 B USD. The appreciable enhancement in the NPV can be justified by the locational indices of the Jakarta and East Java provinces, where high GRP, population density, $PM_{2.5}$ exposure index, and renewable energy supply are present, as explained in the previous sections. Furthermore, this can be demonstrated by the shortest payback period in these provinces.

4. Conclusions

This study proposed an interactive methodological approach that offers a comprehensive quantification overview of the integrated environmental–health–economic co-benefits. This was formulated by implementing renewable electricity generation in Indonesia, considering macroeconomic, demographic, and technical impacts. The distinction of the proposed modelling framework is that it fills the disconnection between the evidence of co-benefits and their incorporation in early planning stages for policy decisions. The current modeling frameworks do not allow for flexible comparisons of co-benefits between different kinds of technologies across different parts of the country.

The synergized air quality improvement, public health co-benefit, economic co-benefit, and cost–benefit assessment in this study are linked to the techno-economic activity parameters of the HRES's electricity. The developed methodological approach allows for stakeholders at the decision- and policy-making level to investigate various climate policies interactively, considering the technical impact and the locational impact of energy production technologies.

The developed methodology was implemented to assess the stated policies scenarios of Indonesia for 2025 and 2030. The acquired local data included geographical and meteorological data from 112 measurement fields covering all the provinces of Indonesia. The technology-wise impact assessment explored the impact of the system's configuration, size, efficiency, and production technology on the integrated co-benefits using six intervention scenarios.

The crucial policy observation in this study was concluded by evaluating the Indonesian STEPS commitments to increase the contributions of renewable energy in the supply energy mix to 23% and 31% by 2025 and 2030, respectively, and reduce 41% of GHG emissions by 2030. The proposed installation capacities of solar PV, wind turbines, and biomass generation throughout the country are 11.5 GW, 0.1 GW, and 0.2 GW, respectively. This has demonstrated the potential co-benefits of exceeding the planned commitments of 2025 and heading to 2030. The proposed scenario predicts a 26.93% contribution of renewable energy to the supply energy mix, compared to the 2020 baseline scenario in which the share of renewable energy is 18.85%. This knocked out the oil and decreased the coal contribution by 5.32%.

The limitations of the developed modeling framework bear in mixing different types of loads and identifying the exact type of load in the residential, commercial, and community load patterns. Instead, the study has provided a default load pattern, which can be adjusted using the country-wide per capita consumption rate. In addition, the application of the developed model should be accomplished by developing a comprehensive database, containing local data on emission factors and relative risk functions to perform a detailed environmental and health assessment.

Future work can be divided into two streams. First, optimally sizing and allocating the supply activity parameters of the HRES considering liberalized electricity markets. The load patterns can be hybridized between different demand patterns, focusing on the type of loads and the potential of demand response application in maximizing the co-benefits. Second, formulating the pathways toward zero emissions and considering the grid constraints of transmissions and distribution infrastructure; resources management including fossil fuel, hydropower, and waste-to-energy resources; and landscape availability for HRES.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli12020023/s1, Figure S1: Representation of the default typical load patterns; Figure S2: The modeling methodology for estimating solar PV electricity; Figure S3: The power coefficient versus the tip speed; Figure S4: Optimal regime characteristic for maxima Cp value; Figure S5: Typical $C_p - \lambda$ curves of different β; Figure S6: A typical wind turbine power output curve; Figure S7: Overall power generation for the wind turbine; Table S1: Total baseline DALYs rates of Indonesia for the selected diseases; Table S2: Technical specifications of the photovoltaics; Table S3: Wood and agricultural feedstocks; Table S4: Technical specifications of the applied wind turbine model; Table S5: Technical specification of the applied battery; Table S6: Emission factors of Indonesia's electricity grid per pollutant; Table S7: Input parameters for the applied scenarios [43–56].

Author Contributions: Conceptualization, H.F. and M.S.S.; methodology, H.F. and M.S.S.; software, M.S.S. and A.N.M.; validation, M.S.S. and A.N.M.; formal analysis, M.S.S. and A.N.M.; investigation, H.F., M.S.S. and A.N.M.; data collection, M.S.S., A.N.M., P.L., N.J. and D.A.P.; writing—original draft preparation, M.S.S.; writing—review and editing, H.F., E.Z., P.L., D.A.P. and N.J.; visualization, M.S.S.; supervision, H.F.; funding acquisition, E.Z. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data acquired for the results presented in this study are explained and cited in the manuscript, Supplementary Materials, and references section.

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Nomenclature

Abbreviations	
ADALYs	Averted Disability-Adjusted Life Years
ALRI	Acute Lower Respiratory Infections
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chronic Obstructive Pulmonary Disease
DALYs	Disability-Adjusted Life Years
GHG	Greenhouse Gas
PGDP	Per capia Gross Domestic Product
GRP	Gross Regional Product per Capita
HRES	Hybrid Renewable Energy System
IEA	International Energy Agency
IHD	Ischemic Heart Disease
LC	Lung Cancer
NDC	Nationally Determined Contribution
NO_x	Nitrogen Oxides
NPV	Net Present Value
PM	Particulate Matter
PV	Photovoltaic
SO_2	Sulfur Dioxide
STEPS	Stated Policies Scenario
Stroke	Cerebrovascular Disease
TB	Tuberculosis And Bronchus
TMY	Typical Meteorological Years
VOCs	Volatile Organic Compounds
Units	
MW	Megawatt
MWh	Megawatt-hour
GW	Gigawatt
GWh	Gigawatt-hour
t	Ton
t/y	Ton per year
USD/t	U.S dollar per year
M USD/y	Million U.S dollars per year
B USD/y	Billion U.S dollars per year
Yrs	Years
Parameters	
A_i	Anisotropy index
R_b	The ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface
β	The slope of the surface
f	The horizon brightening factor
ρ_g	Ground reflectance in percent
T_C	The cell temperature
T_a	The ambient temperature in kelvin
$T_{C,NOCT}$	Nominal operating cell temperature in 317 Kelvin
$T_{a,NOCT}$	The ambient temperature at which the NOCT is defined in 293 Kelvin
α_p	Temperature coefficient of power in percent per Celsius
$T_{C,STC}$	The cell temperature under standard test conditions in 298 Kelvin
τ	The solar transmittance of any cover over the PV array in percent
α	Solar absorptance of the PV array in percent
$\eta_{mp,STC}$	The efficiency of the PV array at its maximum power point under standard conditions in percent
Y_{PV}	The rated capacity of the PV array in kW
f_{PV}	PV derating factor in percent

v	Wind speed in meters per second
v_{cin}	Cut-in speed in meters per second
v_{Co}	Cut-out speed in meters per second
v_r	Rated wind speed in meters per second
C_p	The wind power coefficient
λ	The tip speed ratio
β	The pitch angle
ρ	The air density
A	The swept area by the blades
P_R	The size of the rated power capacity of the battery in kWh
$E_{L,Max}$	The peak demand load in kWh
SOC_t	State of charge of the batteries for the time step of t in kWh
$\dot{Q}$	Steam heat to be supplied to the turbine in Btu
E_{BG_Design}	Biomass generator capacity in kW
$\eta_{steamcycle}$	Steam cycle efficiencies
$e_{fuelmoisture}$	Fuel moisture efficiency loss
$e_{unburnedcarbon}$	Unburned carbon efficiency loss
$e_{drygasloss}$	Dry gas efficiency loss
$e_{latentheat}$	Latent heat efficiency loss
$e_{moistureinair}$	Moisture in air efficiency loss
e_{manu}	Manufacturer efficiency loss
n	Number of residential load units
LAF	Load adjustment factor
hourlypattern	Demand patterns of residential, commercial, or industrial loads
Variables	
$\overline{G_T}$	Solar radiation incident on the PV array in the current time step in kW/m^2
$\overline{G_b}$	Beam radiation in kW/m^2
$\overline{G_d}$	Diffuse radiation in kW/m^2
G_T	Solar radiation striking the PV array in kW/m^2
$\overline{G_{T,NOCT}}$	Solar radiation at which the NOCT is defined as 0.8 kW/m^2
$\overline{G_{T,STC}}$	The incident radiation at standard test conditions in kW/m^2
E_{PVt}	Hourly generated electricity from solar panels in kWh
P_{wind}	The total generated electricity from wind turbines in kWh
E_{WTt}	Hourly generated electricity from wind turbines in kWh
E_{CDt}	Hourly charged or discharged amount of battery energy in kWh
E_{BCt}	Hourly charged amount of battery energy in kWh
E_{BDt}	Hourly discharged amount of battery energy in kWh
$\dot{b}$	Amount of biomass feeding rate in lb/h
HHV	The feedstock gross calorific value
E_{BGt}	Hourly biomass generated electricity in kWh
E_{Gridt}	Hourly electricity sold or purchased from the grid in kWh
E_{Loadt}	Hourly electricity demand in kWh

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