Supplementary material for:

Quantifying the climate co-benefits of hybrid renewable power generation in Indonesia: A multi-regional and technological assessment

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S1: Electric Load Types

The load types in the developed methodology are typical patterns of residential, commercial, and community loads, as depicted in Figure 1S. Equation (1S) aligns the deviation of the default hourly amount of load patterns with the actual per capita capacity consumption by calculating the load adjustment factor. The load adjustment factor is then employed to determine the system's annual demand as expressed in equation (2S).

$$LAF = \frac{PCC}{\sum_{t=1}^{8760} Load\ Pattern} \tag{1S}$$

$$\sum_{t=1}^{8760} Demand = LAF \cdot \sum_{t=1}^{8760} Load\ Pattern \tag{2S}$$

where LAF is the load adjustment factor. PCC is the per capita capacity consumption in Indonesia, which is 1.08 MWh [43]. $Load\ Pattern$ denotes the default hourly load patterns, which can be selected from one of the typical patterns of residential, commercial, or community loads. t is the hourly time step intervals.

On the other hand, the calculation of load units' number for intervention scenarios is calculated based on the annual supply from the HRES to the per capita capacity consumption as expressed in equation (3S). Given this, the hourly annual demand is employed to calculate the load factor, peak, annual, daily, hourly, and average demand. However, the electric load modeling bears a limitation of combining different types of loads. Thus, the investigated intervention scenarios are limited to residential load patterns.

$$Number\ of\ load\ units = \frac{\sum_{t=1}^{8760} HRES\ Supply}{PCC} \tag{3S}$$

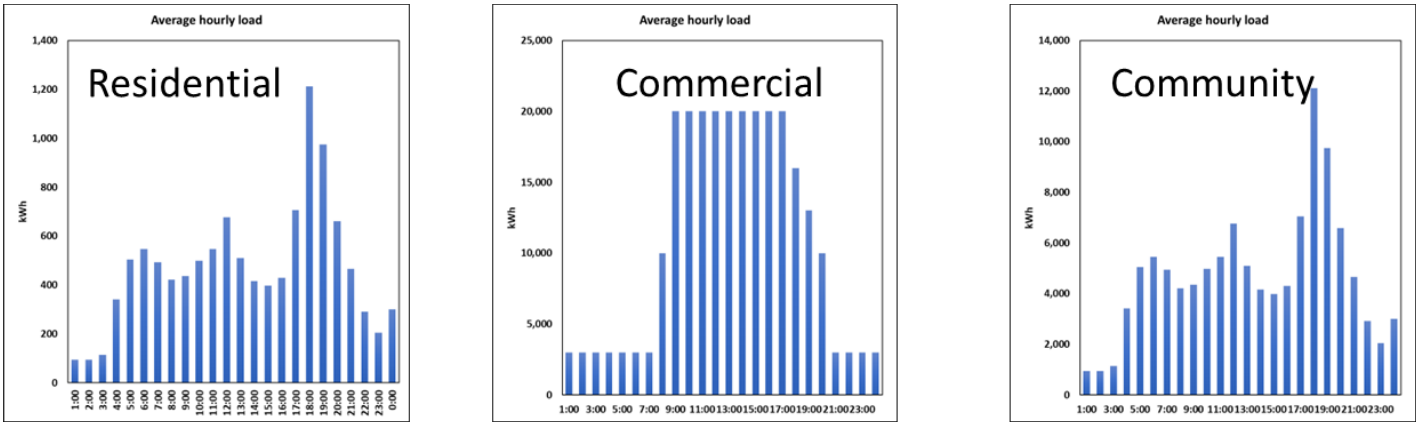

Figure S1. Representation of the default typical load patterns

S2: Solar PV Electricity Generation

The HRES offers four PV arrays: Monocrystalline and three different types of polycrystalline panels. The overall modeling methodology of the solar PV electricity supply is demonstrated in Figure 2S [39]. In this model, the given parameters are the geographical information, metrological data, installed capacity, and slope degree of arrays, while the output power of the PV arrays is calculated as expressed in equation (4S).

$$E_{PV} = Y_{PV} \cdot f_{PV} \cdot \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}}\right) \cdot \left[1 + \alpha_p \left(T_C - T_{C,STC}\right)\right] \tag{4S}$$

where Y_{PV} is the rated capacity of the PV array in kW (i.e., the output power under standard test conditions of 1000W/m^2 luminous intensity, 25°C temperature, and 1.5 air mass). f_{PV} is the derating factor of the PV modules in percent. $\overline{G_T}$ is the incident solar radiation on PV arrays at the current time interval in kW/m^2. $\overline{G_{T,STC}}$ is the standard test conditions of the incident radiation at in kW/m^2. α_p is the power temperature coefficient in %/°C. T_C and $T_{C,STC}$ are the instantaneous PV cell temperature in Celsius and standard test conditions of the cell temperature under in 25°C, respectively.

The equation parameters of (4S) are obtained from the manufacturer's technical specifications according to the PV arrays, as shown in Table 2S in section S8. The $\overline{G_T}$ and T_C are unknown parameters that are to be calculated. Although the ambient temperature is similar to the T_C during the night, the cell temperature may exceed the ambient temperature by 30°C at noon. The hourly precise calculation of T_C is expressed in Equation (5S).

$$T_C = \frac{T_a + (T_{C,NOCT} - T_{a,NOCT}) \cdot \left(\frac{G_T}{G_{T,NOCT}}\right) \cdot \left(1 - \frac{\eta_{mp,STC} \cdot (1 - \alpha_p \cdot T_{C,STC})}{\tau\alpha}\right)}{1 + (T_{C,NOCT} - T_{a,NOCT}) \cdot \left(\frac{G_T}{G_{T,NOCT}}\right) \cdot \left(\frac{\alpha_p \cdot \eta_{mp,STC}}{\tau\alpha}\right)} \qquad (5S)$$

where T_a, $T_{C,NOCT}$, and $T_{a,NOCT}$ are the ambient temperature in kelvin, nominal operating cell temperature in 317 Kelvin, and ambient temperature at NOCT of 293 Kelvin, respectively. G_T and $G_{T,NOCT}$ are the incident solar radiation in the PV array in kW/m^2 and NOCT solar radiation, which is defined as 0.8 kW/m^2, respectively. $T_{C,STC}$ is the cell temperature under standard test conditions in 298 Kelvin. τ and α are the transmittance of any material covering the PV array and the PV array absorptance of solar in percent, respectively. $\eta_{mp,STC}$ is the maximum power point efficiency of PV array under standard conditions in percent, which calculated using equation (6S):

$$\eta_{mp,STC} = \frac{Y_{PV}}{A_{PV} \cdot G_{T,STC}} \qquad (6S)$$

where A_{PV} is the PV array surface in m^2, while $G_{T,STC}$ is equal to 1 kW/m^2.

The precise calculation of the hourly output power from PV arrays necessitates a specific determination of the incident solar radiation received on the tiled surface in the targeted cities of Indonesia. Although climate stations tool up reliable radiation records, normally the provided records contain only the radiation of horizontal surfaces, which lacks the data on tilted surfaces. Total incident radiation on the tilted plane consists of three components: reflected radiation, diffuse radiation, and beam radiation from the ground. Hence, $\overline{G_T}$, the global incident radiation on the PV array calculation is expressed in equation (7S).

$$\overline{G_T} = (\overline{G_b} + \overline{G_d} \cdot A_i) \cdot R_b + \overline{G_d} \cdot (1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + \bar{G} \cdot \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) \qquad (7S)$$

where $\overline{G_b}$ and $\overline{G_d}$ are the beam radiation and the radiation diffused in kW/m^2, respectively. A_i is the anisotropy index[1]. R_b is the radiation of the beam on tilted surface to the beam radiation on the horizontal surface ratio, which is obtained using equation (8S). f is the horizon brightening factor[2] that is calculated using equation (9S). ρ_g is the ground reflectance in percent, which can also be referred to as the albedo. β is the slope of the surface in degrees.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{8S}$$

$$f = \sqrt{\frac{\overline{G_b}}{\bar{G}}} \tag{9S}$$

where $\bar{G}$ is the total of beam and diffuse radiation in kW/m^2, which can be obtained by summing the beam and the diffuse radiations.

To calculate the anisotropy index using equation (10S), $\overline{G_0}$, the averaged horizontal extraterrestrial radiation over the time interval in kW/m^2, and G_{on} is the normal extraterrestrial radiation in kW/m^2 shall be sequentially obtained using equations (11S) and (12S):

$$A_i = \frac{\overline{G_b}}{\overline{G_0}} \tag{10S}$$

$$\overline{G_0} = \frac{12}{\pi} G_{on} \cdot \left[\cos\phi\cos\delta\,(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2-\omega_1)}{180^{\circ}}\sin\phi\sin\delta\right] \tag{11S}$$

$$G_{on} = G_{sc} \cdot \left(1 + 0.033 \cdot \cos\frac{360n}{365}\right) \tag{12S}$$

where ω_1 and ω_2 are the hour angle at the start of the time interval and hour angle at the close of the time interval in degrees, respectively. n is the day number in the year. G_{sc} is the solar constant of 1.367 kW/m^2.

[1] The anisotropy index measures the beam radiation's atmospheric transmittance. It is applied to find the circumsolar diffuse radiation amount, which can be also named the forward scattered radiation.

[2] Horizon brightening factor is applied to reflect the fact that less diffuse radiation comes from the rest of the sky than from the horizon, which can be demonstrated by the cloudiness.

On the other hand, the formed slope[3] angle between the panel surface, the horizontal axis, and the azimuth[4] direction of the panel surface faces are given. Then, sequentially, the declination of solar and the hour angle of the sun location in the sky are calculated using equations (13S) and (14S). For instance, if the obtained hour angle is equal to 15, the sun movement is 15° per hour across the sky.

$$\delta = 23.45° \cdot \sin\left(360° \cdot \frac{284+n}{365}\right) \quad (13S)$$

$$\omega = (t_s - 12\text{hr}) \cdot 15\ {}^{°}/_{\text{hr}} \quad (14S)$$

where δ is the declination of the solar in degrees. n is the day number in the year. ω is the hour angle in degrees. $t_s$is the solar time in hour, which can be obtained using equation (15S). This necessitates an advanced calculation for the equation of time as expressed in (16S):

$$t_s = t_c + \frac{\lambda}{15°/\text{hr}} - Z_C + E \quad (15S)$$

$$E = 3.82(0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B - 0.014615 \cdot \cos 2B - 0.04089 \cdot \sin 2B) \quad (16S)$$

$$B = 360° \cdot \frac{(n-1)}{365} \quad (17S)$$

where $t_c$is the civil time in hourly intervals, which corresponds to the time intervals' midpoint. λ is the location's longitude in degrees. $Z_C$is the east of GMT time zone in hours. E is the equation of time in hours. Eventually, the angle of incidence can be obtained for any surface orientation using equation (18S) as follows:

$$\cos\theta = \sin\delta \cdot \sin\phi \cdot \cos\beta - \sin\delta \cdot \cos\phi \cdot \sin\beta \cdot \cos\gamma + \cos\delta \cdot \cos\phi \cdot \cos\beta \cdot \cos\omega + \cos\delta \cdot \sin\phi \cdot \sin\beta \cdot \cos\gamma \cdot \cos\omega + \cos\delta \cdot \sin\beta \cdot \sin\gamma \cdot \sin\omega \quad (18S)$$

[3] If the slope = 0, it means that the PV array is in a horizontal orientation, while if the slope=90°, the PV array is in a vertical orientation.

[4] If the azimuth = 0, it corresponds to the south orientation; west-facing orientations are indicated by positive values, -45° indicates the southeast-facing orientations, while 90° shows the west-facing orientation.

where θ, β, and γ are the angle of incidence, the slope of the surface, and the azimuth of the surface in degrees, respectively. ϕ, δ, and ω are the latitude, solar declination, and hour angle in degrees, respectively. θ_z is the zenith angle in degrees, which can be obtained using equation (19S).

$$\cos\theta_z = \cos\phi \cdot \cos\delta \cdot \cos\omega + \sin\phi \sin\delta \tag{19S}$$

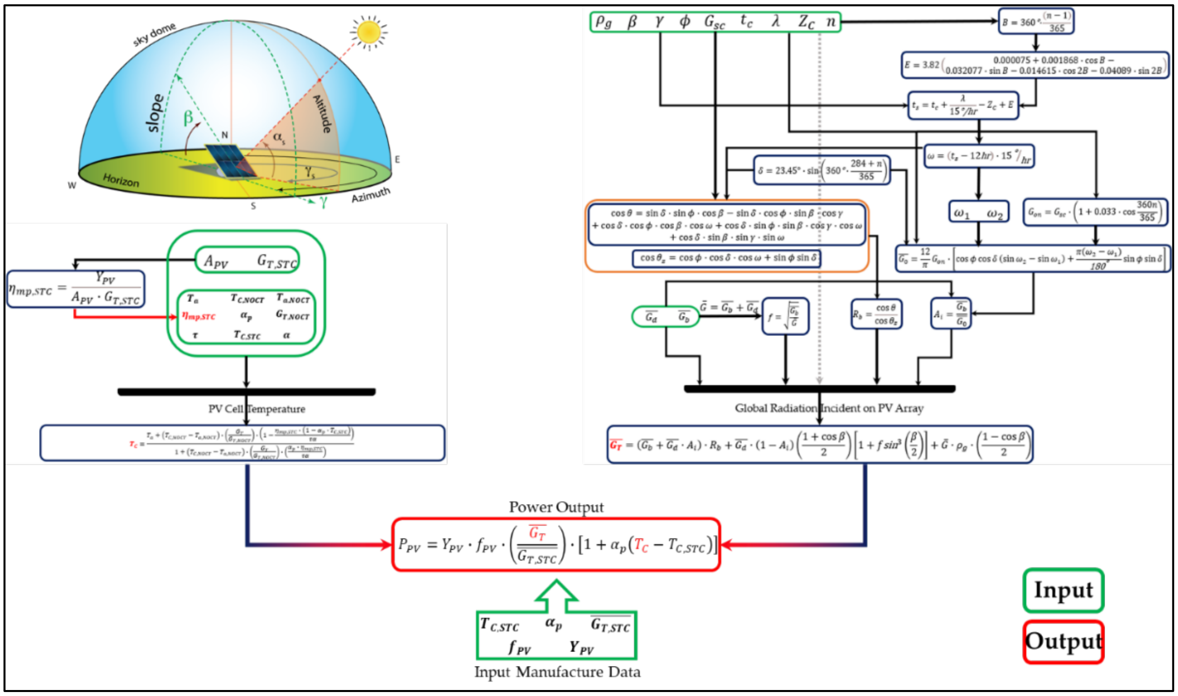

Figure S2. The modeling methodology for estimating solar PV electricity [39].

S3: Wind Turbines Electricity Generation

The HRES tool offers 379 wind turbines classified per manufacturer, rated capacity, blade diameter, rated velocity, and cut-in velocity. The data inventory for the offered wind turbines was acquired from [44]. The turbines were configured to generate the maximum power at both minimal wind speed and cost incurred in construction, whereas the overall calculation methodology explained in this section was customized based on [45]. In this model, the ideal condition where the turbine blades capture all flowing wind is expressed in the equivalent electric power output using equation (20S).

$$E_{WTt} = C_p P_{in} \quad (20S)$$

where P_o is the electric power output from the wind turbine. C_p denotes the coefficient of power due to the wind turbine rotor's aerodynamic efficiency, which is a function of the tip speed ratio and pitch angle. P_{in} is the mechanical wind power harnessed by the turbine as calculated using equation (21S). This relies on the Rankine–Froude model, accounting for rotational flow with emphasis on propellers; the power through a cross-sectional area is normal to the swept wind by the rotor blades. Equation (22S) expresses the substitution of the harnessed wind mechanical power of (21S) into (20S), considering the tip speed ratio and pitch angle.

$$P_{in} = \frac{1}{2}\rho A v^3 \quad (21S)$$

$$E_{WTt} = \frac{1}{2} C_p(\lambda, \beta) \rho A v^3 \quad (22S)$$

where ρ is the air density. A is the blades' swept area. v is the wind speed in m/s. λ and β are the tip speed ratio and pitch angle, respectively. The tip speed ratio can be obtained using the ratio between the fringe speed of the blades and the wind speed as expressed using equation (23S).

$$\lambda = \frac{\Omega R}{v} \quad (23S)$$

where Ω is the rotational speed of the blades in radians per second. R is the blade radius and v is the free stream velocity of the wind. The value of the power coefficient as a function of tip speed ratio and pitch angle can be obtained as expressed in equation (24S).

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \quad (24S)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (25S)$$

A typical performance curve for the horizontal axis wind turbine (HAWT) is depicted in Figure 3S [46]. This shows an optimal λ for a well-determined tip speed ratio, denoted by λ_{opt}. According to the correlation of the rotational speed of the blades with the wind power coefficient, the power characteristics have the form of an inverted U curve, as shown in Figure 4S. This has a maximum for each wind speed corresponding to the maximal value of C_p, whereas an optimal regime characteristic for maxima C_p value is achieved.

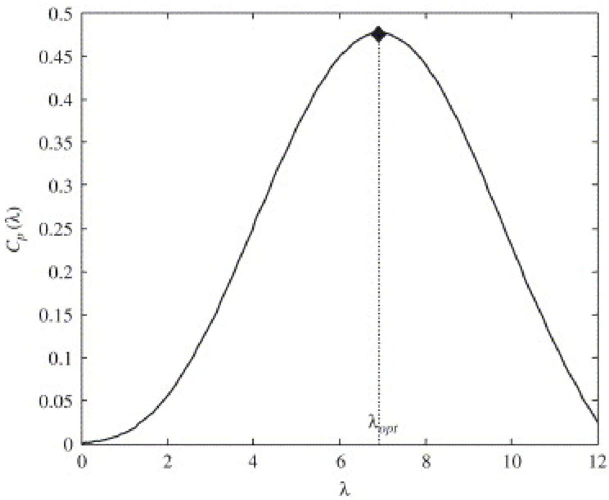

Figure S3. The power coefficient versus the tip speed [46].

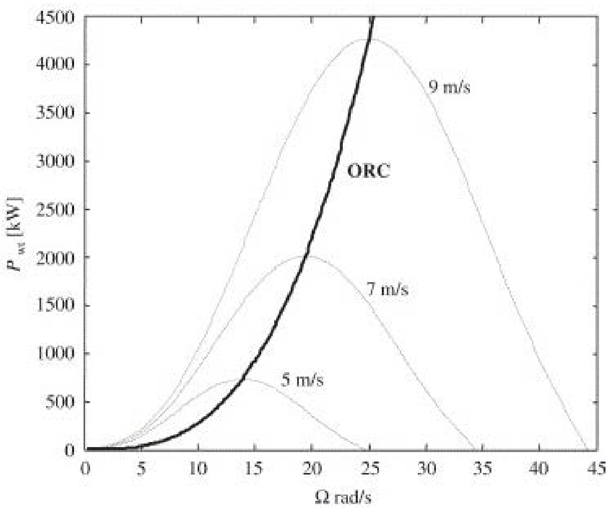

Figure S4. Optimal regime characteristic for maxima Cp value [46].

Based on the dependency on the λ and β, the maximum value of C_p can be reached and maintained by controlling the pitch angle and generator speed at a given wind speed. Figure 5S shows an assortment of typical C_p-λ curves for different β. This shows there is always a maximum value for C_p at a stated wind speed.

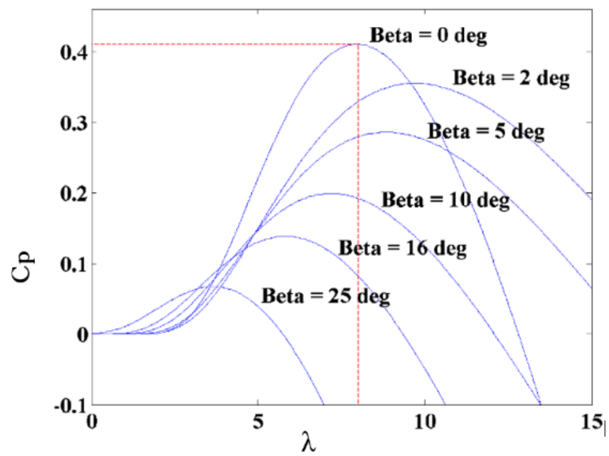

Figure S5. Typical $C_p - \lambda$ curves of different β [47].

The total wind power is extracted according to the specified wind turbine type, where the wind speed of a given location at reference height, cut-in speed (i.e., minimum limit of electricity generation), cut-out speed (i.e., the maximum limit of electricity generation), and rated speed are given. This is mathematically calculated using condition (26S).

$$P_{wind} = \begin{cases} E_{WTt}\left(\frac{v-v_{Cin}}{v_r-v_{Cin}}\right), & v_{cin} \leq v \leq v_r \\ E_{WTt}, & v_r \leq v \leq v_{Co} \\ 0, & v \leq v_{Cin}, v \geq v_{Co} \end{cases} \tag{26S}$$

$$v = v_{ref}\left(\frac{H}{H_{ref}}\right)^{\alpha} \tag{27S}$$

where P_{wind} is the total generated electric power in kWh. v refers to the wind speed in meter per second for the defined height of H. v_{cin}, v_{Co}, and v_r refer to the cut-in speed, cut-out speed, and rated wind speed in meter per second, respectively. v_{ref} denotes the measured wind speed at the reference height in meter. H_{ref} is the reference height in meter. α is the power-law exponent. The relationship expressed in condition (26S) is illustrated in Figure 6S to show a typical wind turbine curve.

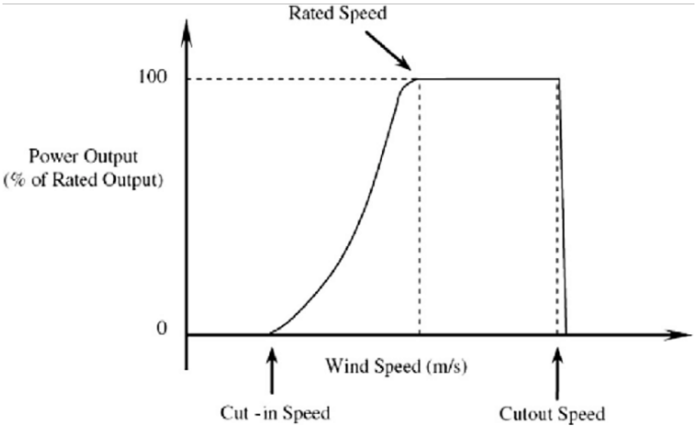

Figure S6. A typical wind turbine power output curve.

The hourly generated wind power according to a given wind turbine type and manufacturer datasheets for a given location is calculated. The modeling equations of the overall power generated from the wind turbines is shown in Figure 7S.

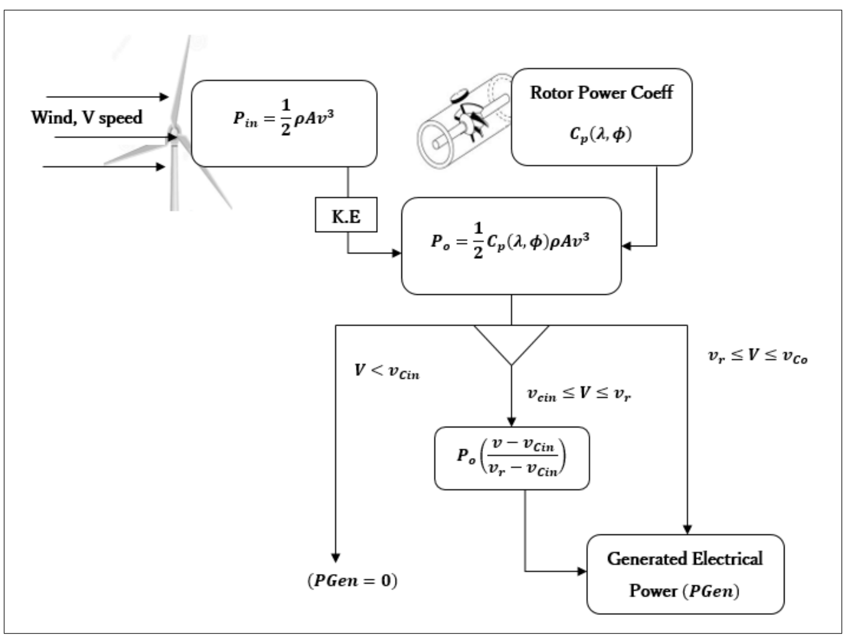

Figure S7. Overall power generation for the wind turbine.

S4: Biomass Electricity Generation

The HRES offers two types of biomass electricity supply technologies based on the feedstock categories. These are classified into the combustion of wood and agricultural feedstocks and waste-to-energy (WtE) incineration technology using municipal solid waste (MSW). The biomass electricity supply is estimated as modeled in [48]. However, the modeling approach is specially customized to align with the overall HRSE objective. In this model, the parameters are geographical information, metrological data, biomass feedstock type, generation plant capacity, and combustion system. The energy and mass balance are modeled to obtain the hourly electricity output from biomass.

S4.1: Feedstock Type:

The elemental composition of the biomass feedstock, mass fraction, net calorific value (i.e., low heating value (LHV)), gross calorific value (i.e., high heating value (HHV)), and dry basis moisture content of the selected feedstock type are obtained from [49]. The model imports the feedstock's elemental composition and dry moisture content based on the given geographical location and feedstock type. The monthly ambient temperature and relative humidity are calculated using equations (28S) and (29S), respectively.

$$T_A = \frac{\sum_{n=0}^{N\times 24} T_n}{N\times 24} \tag{28S}$$

$$r = \frac{\sum_{n=0}^{N\times 24} r_n}{N\times 24} \tag{29S}$$

where T_A is the ambient temperature in Celsius. T_n is the temperature of the nth hour at the month in Celsius. n is the number of monthly hours, while N denotes the number of days in the month. r is the relative humidity in percent, and r_n is the relative humidity of the nth hour of the month in percent.

The wet basis moisture content of the specified feedstock is calculated using equation (30S), while the elemental composition of the feedstock, mass fraction, LHV, HHV, and M_{db} of the specified feedstock type are shown in Table 3S in section S8.

$$M_{wb} = \frac{M_{db}}{(1+M_{db})} \tag{30S}$$

where M_{wb} and M_{db} are the wet and dry basis moisture content in percent, respectively.

Depending on the availability of comprehensive data sets, the HHV can alternatively be obtained for any feedstock type using equation (31S) or (32S).

$$HHV = LHV + 10.30\,(H_2 \times 8.94) \tag{31S}$$

$$HHV = 3.55C^2 - 232C - 2{,}230H + 51.2C \times H + 131N + 20{,}600 \tag{32S}$$

where HHV and LHV are the high and low heating value in British thermal units per pound (Btu/lb), respectively. H_2 is the fuel diatomic hydrogen in mass percent. H, C, and N are the hydrogen, carbon, and nitrogen dry biomass weight percent, respectively.

S4.2: Generating Capacity and Combustion Type

The HRES offers four types of combustion systems for the wood and agricultural feedstocks, which serve from a scale of 1 kW up to 150 MW with various output efficiencies. This comprises Bed combustors such as fluidized-bed combustors and fixed-bed combustors, which are the most expensive solutions in terms of capital cost, operational, and maintenance costs. Meanwhile, the most efficient solutions are output power and environmental pollution. The cyclone combustors are suitable for low-scale capacities, while the output power and environmental pollution efficiency are slightly lower than bed combustors. Lastly, the great stokers combustors are generally the least expensive solutions, offering the least efficiency [50]. On the other hand, for WtE incineration, the HRES offers fluidized-bed combustors and great stokers combustors as the most popular technologies.

S4.3: Energy Balance

The energy balance calculation follows the Btu method as described in [50]. To obtain the energy balance, the efficiency losses of moisture in fuel, unburned fuel, dry flue gas losses, latent heat, moisture in the air, and miscellaneous manufacturing losses are estimated. The moisture in fuel losses is calculated using equation (33S).

$$e_{fuel\ moisture} = M_{db} \frac{(H_2 - H_1)}{HHV} \quad (33S)$$

where $e_{fuel\ moisture}$ is the moisture in fuel losses in percent. H_1 and H_2 are the water's enthalpy of the biomass at pre-combustion and the vaporized moisture enthalpy of the stack steam in Btu/lb calculated using equations (34S) and (35S), respectively.

$$H_1 = T_A - 32 \quad (34S)$$

$$H_2 = (0.00003958 T_{FG} + 0.4329) T_{FG} + 1{,}062.2 \quad (35S)$$

where T_A is the ambient temperature in Fahrenheit. T_{FG} is the steam leaving the stack temperature at the flue gas temperature in Fahrenheit.

The unburned fuel depends on the boiler type, which is a consequence of incomplete combustion due to the excess air amount. For well-maintained boilers and at acceptable excess air levels, the unburned fuel varies according to the technology, as demonstrated in equation (36S) [51].

$$\eta_{unburned\ carbon} = \begin{cases} 3.5\%\ for\ stoker\ boilers \\ 0.25\%\ for\ FBC \\ 3.0\%\ Cyclone \end{cases} \quad (36S)$$

where $\eta_{unburned\ carbon}$ is the losses due to the unburned carbon in the fuel.

The dry gas's mass flow rate is calculated using equation (37S). Sequentially, the dry flue gas loss is calculated based on the temperature difference of the inlet air and the outlet steam leaving the stack at flue gas temperature in Fahrenheit, as expressed in equation (38S).

$$\dot{n} = \left(\left((12.7C + 38.1H) \times (1 + \frac{a}{100}\right) - 0.5O\right) \frac{1}{HHV} \quad (37S)$$

$$e_{dry\ gas\ loss} = 24 \times (T_{FG} - T_A)\ \dot{n} \tag{38S}$$

where $\dot{n}$ is the dry gas's mass flow rate in pounds per Btu fuel. a is the excess fed air based on the combustion system type in percent.

The latent heat losses generated due to the chemical reaction of the free hydrogen with the oxygen during the combustion are estimated from the generated steam during the combustion process using equation (39S).

$$e_{latent\ heat} = \frac{H \times 100 \times 8.94}{HHV} \quad (H_2 - H_1) \tag{39S}$$

where $e_{latent\ heat}$ is the latent heat efficiency in percent to the total input heat. H_1 and H_2 are the water's enthalpy as calculated in equation (34S) and (35S), respectively.

The moisture in air losses is the spatiotemporal effect that varies with the geographical location and hourly climate parameters. In this model, the moisture in air losses is calculated using equation (40S).

$$e_{moisture\ in\ air} = 45 \times \dot{n}\left(0.622 \times \left(\frac{(0.01 \times r \times P_{vd}}{P_b - (0.01 \times r \times P_{vd})}\right)\right)(T_{FG} - T_A) \tag{40S}$$

where $e_{moisture\ in\ air}$ is the moisture in air efficiency in percent. r is the relative humidity obtained in (29S). $\dot{n}$ is the mass flow rate of the dry gas obtained in (37S). P_b denotes the barometric pressure, while P_{vd} is the saturated absolute pressure as calculated using equation (41S):

$$P_{vd} = 0.0886e\left(\frac{17.2694T_c}{T_c + 238.3}\right) \tag{41S}$$

where P_{vd} is the water vapor's absolute saturated pressure in psi. T_c is the ambient temperature in Celsius.

Lastly, the manufacturer's margin losses are all lumped together. This includes radiation in the ash pit, sensible heat in ash, and sensible heat in flue dust. In this model, the manufacturer's margin losses are denoted by e_{manu} are assumed 2.03 [51].

S4.4: Mass Balance

The combustion system's mass balance is obtained through two material balances: the boiler steam and the stream of the biomass. After the vaporization at the combustion stage, the useful heat is transferred to the feedwater at the boiler stream. Hence, since the generating plant capacity is given, the amount of the heat is calculated by conversion of the generating capacity from kW to Btu and considering steam cycle and energy balance efficiencies as follows:

$$\dot{Q} = \frac{O_{Design} \times 3{,}412.14}{\eta_{steam\ cycle}} \times \left(\frac{\left(100-\left(e_{fuel\ moisture}+e_{unburned\ carbon}+e_{dry\ gas\ loss}+e_{latent\ heat}+e_{moisture\ in\ air}+e_{manu}\right)\right)}{100}\right) \quad (42S)$$

where $\dot{Q}$ is the steam heat to be supplied to the turbine in Btu. O_{Design} is the generating capacity in kW. The 3,412.14 is the kW to Btu conversion factor, while $\eta_{steam\ cycle}$ denotes the steam cycle efficiencies normally assumed to be around 40%. $e_{fuel\ moisture}$, $e_{unburned\ carbon}$, $e_{dry\ gas\ loss}$, $e_{latent\ heat}$, $e_{moisture\ in\ air}$, and e_{manu} are the efficiency losses representing the heat loss due to the energy balance. Using the obtained steam heat to be supplied to the turbine, the biomass feeding rate can be calculated using equation (43S).

$$\dot{b} = \frac{\dot{Q}}{HHV \times \left(\frac{\left(100-\left(e_{moisture\ in\ air}+e_{latent\ heat}+e_{fuel\ moisture}+e_{manu}+e_{rad}+e_{dry\ gas\ loss}\right)\right)}{100}\right)} \quad (43S)$$

where $\dot{b}$ is the amount of biomass feeding rate in lb/hr. HHV is the feedstock gross calorific value. Consequently, by obtaining the heat transferred to the feedwater boiler and biomass feeding rate, the net annual biomass generated electricity is calculated as expressed in equation (44S).

$$O_{net} = \frac{\left(\sum_{0}^{8760} \dot{Q} \times \eta_{steam\ cycle} \times t\right)}{3{,}412.14} \quad (44S)$$

where O_{net} is the net annual output of the biomass generator in kWh. t denotes the time interval of one hour.

S4.5: Biomass output parameters

The power plant's parasitic load is the self-consumption required by the operation (i.e., pumps, electronic control, motors, and on-site miscellaneous loads), which is usually assumed to be between 10 to 15 percent [52]. This study considers the parasitic 10 percent load of the net generated electric energy. The total generated energy in kWh is calculated considering the net generated power and parasitic load from the relation expressed in equation (45S).

$$O_{net} = O_{gross} \times \left(1 - \frac{P}{100}\right) \quad (45S)$$

where O_{gross} is the total generated energy in kWh, and O_{net} is the net generated energy considering the parasitic load P in percent. On the other hand, the heat rate (MMBtu/MWh), thermal efficiency in percent, capacity factor in percent, hourly net generated energy in kWh, and the annual generated energy in kWh are calculated using equations (46S) to (50S), respectively.

$$HR_{gross} = \frac{\dot{b} \times HHV}{O_{net} \times 1000} \quad (46S)$$

$$HR_{net} = \frac{\dot{b} \times LHV}{O_{net} \times 1000} \quad (47S)$$

$$\eta_{therm,HHV} = \frac{341.23}{HR_{gross}} \quad (48S)$$

$$\eta_{therm,LHV} = \frac{341.23}{HR_{net}} \quad (49S)$$

$$CF = \frac{O_{net}}{C_{design} \times 8760} \quad (50S)$$

where the gross heat rate HR_{gross} in MMBtu/MWh is calculated using equation (46S), considering the amount of biomass feeding rate in lb/year, HHV, and the net annual output energy. Equation (47S) calculates the net heat rate HR_{net} in MMBtu/MWh, considering the LHV. Furthermore, the thermal efficiency at HHV $\eta_{therm,HHV}$ and at LHV $\eta_{therm,LHV}$ are calculated using equations (48S) and (49S), in percent, respectively. Eventually, the capacity factor in percent is calculated.

S5: Energy Storage Cycles of Electric Batteries:

The charging and discharging cycles are based on the given technology and initial charging state. The energy storage of electric batteries is restricted to off-grid mode and with disabled biomass generation. The conditions of charging and discharging cycles are expressed in equations (51S) and (53S), respectively.

$$E_{PV_t} + E_{WT_t} > E_{Load_t} \tag{51S}$$

$$E_{PV_t} + E_{WT_t} < E_{Load_t} \tag{52S}$$

$$E_{CD_t} = E_{PV_t} + E_{WT_t} - E_{Load_t} \tag{53S}$$

where $E_{PV_t}$is the hourly generated electricity from solar panels for the time step of t in kWh. $E_{WT_t}$is the hourly generated electricity from wind in kWh. $E_{Load_t}$is the hourly electricity demand in kWh. $E_{CD_t}$is the charged or discharged amount of battery energy, whereas the negative sign indicates the discharging direction. The surplus power from the renewable energy supply aims to charge the batteries, while during the supply shortage, the batteries discharge to support the renewable energy supply. The rated power of the battery energy storage is sized based on the peak load of the HRES as expressed in equation (54S). The batteries' state of charge is constrained to be between a minimum discharging level of more than 20% and a maximum charging of below 80% to maximize the efficiency and lifetime of the batteries. Hence, the hourly state of charge is calculated as formulated in equation (54A) [53].

$$P_R = \frac{E_{L,Max} \cdot AD}{DOD.\eta_b} \tag{54S}$$

$$20\% < SOC_t < 80\% \tag{55S}$$

$$SOC_t = SOC_{t-1} + \frac{E_{CD_t}\eta_{inv}}{P_R} \tag{56S}$$

Where P_R is the size of the rated power capacity of the battery in kWh. $E_{L,Max}$ is the demand peak load in kWh. AD is the autonomy days of the batteries, which is the time period the battery can meet the demand without a charging event. The sizing of all battery technologies is modeled by considering three days of autonomy. DOD is the depth of discharge in percent, which varies according to the technology and manufacturer. Table 5S in section S7 shows the technical specification of the applied battery. η_b and η_{inv} are the battery round-trip efficiency and inverter efficiency in percent, respectively.

S6: Pollutant concentrations change using dispersion model

The dispersion model employs a steady-state Gaussian depression model to estimate the hourly concentration in downwind distance, x, in km and the crosswind distance, y, in km [24].

$$C = \frac{QH}{2\pi v_s \delta_y \delta_z} exp\left[-0.5\left(\frac{y}{\delta_y}\right)^2\right] \quad (57S)$$

$$H = \left[exp\left(-0.5\left(\frac{z-h}{\delta_z}\right)^2\right)\right] + \left[exp\left(-0.5\left(\frac{z+h}{\delta_z}\right)^2\right)\right] \quad (58S)$$

$$\delta_y = 465.12xtan(0.0174(\theta - \mu\, ln(x)) \quad (59S)$$

$$\delta_z = \partial x^{\rho} \quad (60S)$$

$$v_s = v_0\left(\frac{H}{z_0}\right)^p \quad (61S)$$

where, C is the concentration in g/m3. E is the emission rate of the pollutant. v_s is the average wind speed at the height of release in m/s. z is the height of the receptor in meters. δ_y and δ_z are the standard deviation of concentration distribution for the lateral and vertical in meter, respectively. h is the height of the effective source, with respect to the vertical distance between the ground and exhaust pipe. θ , μ , ∂ and ρ are the constant coefficients, which are defined according to the given values of the local area's stability category. x is the source distance in meters.

S7: Baseline DALYS of the specific diseases

Table S1. Total baseline DALYs rates of Indonesia for the selected diseases.

Disease	DALY
Chronic Obstructive pulmonary Disease (COD)	663
Ischemic Heart Disease (IHD)	2553
Cerebrovascular Disease (Stroke)	2755
Lung Cancer (LC)	590
Acute Lower Respiratory Infections (ALRI)	517
Tuberculosis and Bronchus (TB)	590

S8: Technical data used in the HRES calculation

Table S2. Technical specifications of the photovoltaics.

Specs.	Poly-crystalline	Mono-crystalline
Nominal operation cell temperature (°C)	45	44
Nominal operation ambient temperature (°C)	25	25
Incident radiation under nominal condition (kW/m^2)	1	1
Incident radiation under test condition (kW/m^2)	1	1
Surface Area (m^2)	1.96	1.85
Rated power (kW)	0.335	0.41
Maximum efficiency (%)	0.1711	0.222
Standard Temperature (0C)	25	25
Temperature coefficient of Voc (%/deg)	-0.31	-0.24
Solar transmittance	0.9	0.9
Derating factor	0.807	0.92
Model Reference Number	AE7P335VB5B	EVPV410HK
Ref.	[54]	[55]

Table S3. Wood and agricultural feedstocks [49].

Feedstock Type	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	HHV dry (MJ/kg)	LHV dry (MJ/kg)
Wood, excess fraction wood from an organic domestic waste composting plant	29.01%	3.26%	23.84%	0.89%	0.15%	11.12	10.41
Grass Pellets I	44.14%	5.60%	35.64%	2.50%	0.22%	18.57	17.35

Cotton gin waste	49.03%	4.71%	35.08%	1.45%	0.36%	16.27	15.24
Straw pellets char	42.50%	1.40%	5.04%	0.80%	0.49%	20.20	19.89
Char from wheat straw I	54.19%	1.40%	4.95%	0.89%	0.07%	16.31	16.00
Char from wheat straw II	66.40%	2.70%	11.10%	0.60%	0.00%	25.18	24.59
Wheat Straw	46.26%	5.89%	39.58%	0.99%	0.16%	17.68	16.39
Banagrass	48.79%	5.57%	42.60%	0.31%	0.05%	18.60	17.38
Grass	46.44%	5.10%	37.58%	1.33%	0.09%	18.19	17.04
Grass from the nature reserve	45.60%	6.10%	39.30%	1.47%	0.19%	18.24	16.91
Grass Pellets II	39.07%	4.96%	31.54%	2.22%	0.41%	16.45	15.09
Reed Canary Grass	42.08%	5.16%	37.65%	0.36%	0.04%	17.16	15.80
Rice hulls	34.83%	4.37%	30.81%	0.21%	0.28%	12.25	11.10
Rice Husk	35.03%	5.00%	34.15%	0.32%	0.02%	14.40	13.07
Rice Shell	39.71%	4.94%	34.07%	49.00%	8.00%	15.72	14.54

Table S4. Technical specifications of the applied wind turbine model [44].

Turbine Module	Rated Power (kW)	Diameter (m)	Rated Velocity (m/s)	Cut-in Velocity (m/s)
Mitsubishi MWT-62/1.0	1,000	61.4	12.5	3

Table S5. Technical specification of the applied battery [56].

Battery Technology	DOD (%)	Cycles	Discharge Rate in 24 Hrs	Efficiency (%)
Lead Acid GEL Battery	40	1200	15%	76

Table S6. Emission factors of Indonesia's electricity grid per pollutant [37]

Pollutant	Emission Factor (g/kWh)
CO_2	971.511
N_2O	0.017
CH_4	0.115
$PM_{2.5}$	0.178
CO	0.140
SO_2	12.000
NO_x	4.360

Table S7. Input parameters for the applied scenarios

Scenario	Province	Residential Load Units Number	Population	GRP ($)	$PM_{2.5}$ Index ($\mu g/m^3$)	Energy Storage Capacity (MWh)	Solar Installed Capacity (MW)	Wind Installed Capacity (MW)	Biomass Installed Capacity (MW)
S1	Bali	2,400	3,890,757	3,741	10.75	8	0.1	2	-
S2	Bali	2,400	3,890,757	3,741	10.75	-	0.1	2	-
S3	Bali	1.04M	3,890,757	3,741	10.75	-	500	100	-
S4	Bali	1.64M	3,890,757	3,741	10.75	-	500	100	100
S5	Jakarta	5.80M	9,607,787	20,093	32.08	-	3000	-	100
S6	Jakarta	5.42M	9,607,787	20,093	32.08	-	3000	-	100
S7	Aceh	7.28M	4,494,410	2,637	14.30	-	4000	-	-
S8	East Java	7.33M	37,476,757	4,469	17.93	-	4000	-	-