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3E-Analysis of a Bio-Solar CCHP System for the Andaman Islands, India—A Case Study

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Abstract: Energy services are especially expensive on remote islands due to longer and more unstable fuel supply chains. In this paper, different renewable energy systems utilizing locally available biomass and solar energy are proposed as alternatives for a hotel resort on Neil Island, India. Based on local demand data, commercial information, and scientific literature, four cases are modelled with the simulation software HOMER and their economic, energetic, as well as ecological (3E) performances are compared. The robustness of each case configuration is tested with a sensitivity analysis. The results show that a biomass-based, solar-assisted combined cooling, heating, and power (CCHP) system offers an economic saving potential of more than 500,000 USD over twenty years and could decrease CO_2 emissions by 365 t per year. When not applying CCHP measures, system performance is significantly worsened. A solar and battery-assisted diesel generator system shows similar economic outcomes as the CCHP system but worse ecological performance. Implementing the biomass-based CCHP system could improve the ecological footprint of the island, substantially decrease expenditure for the hotel owner, and generate a new source of income for surrounding farmers through biomass selling.

Keywords: renewable energy; biomass gasification; bio-solar; small-scale CCHP

1. Introduction

Due to escalating greenhouse gas (GHG) levels and the consequential climate change, higher sea levels as well as more extreme weather events have been observed and a further increase has been predicted [1]. These phenomena are especially threatening for islands and island states, where approximately 10% of the world's population are living [2]. Additionally, smaller islands tend to rely heavily on diesel-fuelled mini-grids, although the necessary oil is rarely extracted on the same islands [3]. This often leads to high electricity prices, unstable electricity supply and water shortages, which in turn promotes social, economic, and political instability within the islands' communities [4,5]. However, many islands offer vast potential for renewable energies like solar, wind, hydro, and/or biomass [6]. By seizing the potential of these energy resources, the island inhabitants could raise their energy autonomy, while improving their ecological footprint.

To achieve not just ecological, but also economic, superiority these systems can be designed and installed using combined cooling, heat, and power (CCHP) technology to provide several energy services while benefitting from an augmented overall system efficiency [7]. Many researchers argue that the most important component of a CCHP system is the heat engine or prime mover, where electricity and heat are generated [8,9]. Apart from the prime mover, many different technologies have to be selected for the design of CCHP systems; these are, amongst others, thermal cooling devices, heat exchangers, batteries, thermal storage facilities, and system control units [9,10]. When CCHP systems are driven with biomass, additional technologies for the biomass conversion are necessary. In combination with internal combustion engines, gasification is considered as the optimal choice for woody plant residues due to the high conversion efficiency and the high producer gas quality [11]. India is currently leading in total capacity of small gasifiers for electricity generation and actively supporting gasification technologies for off-grid renewable energy systems [12].

There are some studies investigating, renewable small-scale CCHP systems on islands. Calise et al. [13] simulated an ingenious polygeneration system seizing geothermal as well as solar energy to provide electricity, heating, cooling, and potable water for the volcanic island of Pantelleria in the southern Mediterranean Sea. Concentrating photovoltaic/thermal solar collectors could provide 800 kW peak electric power with space heating capacities of 700 kW, cooling capacities of 900 kW, and hot domestic water with a nominal capacity of 3900 kW. The system could also generate 2.71 kg/s of potable water using the heat from the solar and the geothermal systems. This translates into savings of nearly 5000 t of CO_2 emissions/year and production of 41,800 t/year of fresh water. The payback period was calculated to be less than four years. In a similar system, they substitute the geothermal well with a biomass fed auxiliary boiler and obtain similar results [14]. Another thermo-economic analysis of a small-scale CCHP system situated on a Greek island was presented by Karellas et al. [15]. An Organic Rankine Cycle (ORC) driven by a biomass boiler and solar-thermal collectors could provide 1.42 kW of electricity and around 50 kW of thermal power. The estimated payback period varied between four and 18 years depending on the capital investment costs and biomass price but would outperform the reference system in all cases. Chua et al. [16] investigated different CCHP system configurations with a variety of different prime mover technologies (microturbines, a solar Stirling dish, a fuel cell system, and an ORC) in assistance with PV panels and wood chip biomass. The systems were designed for the touristic island of Pulau Ubin, Singapore. Among combinations of all the different technologies, the economically optimal case would lead to a 20% renewable energy penetration and save up to 1000 tons of CO_2-eq/year.

These previous works show the increasing interest and research conducted in small-scale, renewable energy CCHP systems for islands. However, despite the many advantages of renewable CCHP systems, the application of such systems is spreading only slowly [17]. This may be due to insufficient knowledge about the availability of such technologies, too many uncertainties for investors, and/or too much complexity for system operation and maintenance [3,7]. To improve the life quality of island inhabitants and to reduce the dependency on fossil fuels worldwide, it is necessary to quantify the main benefits of individual CCHP systems, especially on islands, and to identify the main challenges as well as key drivers for further development. In this context the combination of biomass and solar as primary energy sources for small-scale CCHP systems is promising: both resources are available locally; biomass can be readily employed for base load operation when considering thermochemical conversion processes; and solar energy with batteries can support the system to cover peak loads.

Until now, there is yet to appear an investigation that places these aspects in a remote island setting with due care taken to technical and socio-economic parameters. Therefore, the aim of this study is to quantify the benefits and drawbacks of an innovative small-scale, renewables-based CCHP system via a case study of the Andaman Islands, India. The integration of PV and battery storage with a syngas-fuelled engine represents a novel feature of the CCHP system. Energetic, economic and ecologic performance of various configurations are compared to a fossil fuel-based reference system, all providing energy services to a hotel resort for a typical year of operation. To further close the gap in literature, the system is put into a wider socio-economic context with respect to the primary stakeholders (operator, customers, and other interest groups).

After this introduction, the different sources of data are listed in Section 2 and the methodology applied is explained. The model as well as the system components used within the model are described in Section 3. The results are presented in Section 4. In Section 5, the results are discussed and conclusions are drawn in Section 6.

2. Methodology and Data Acquisition

2.1. Methodology

The system configurations are modelled using the Hybrid Optimization of Multiple Energy Resources (HOMER) software (HOMER Legacy, version 2.68 beta, HOMER Energy LLC, Boulder CO 80304, USA), which is a powerful tool to optimize renewable energy systems according to their economic performance over a certain lifetime [18,19]. Based on input data, HOMER simulates various system configurations according to a search space and lists feasible solutions that conform to the pre-set system requirements and limitations. For this, HOMER computes the system performance for every hour of the given project lifetime. Feasible solutions are listed according to their Net Present Cost (NPC); hence, it is an economic optimization. HOMER uses the following equations to calculate the *NPC*:

$$NPC = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{1}$$

$$CRF(i, R_{proj}) = \frac{i(1+i)^R}{(1+i)^R - 1} \tag{2}$$

where $C_{ann,tot}$ is total annualized costs and CRF is the capital recovery factor with i being the interest rate (in the simulation: 6% based on historical values from 2000–2018 [20]) and R_{proj} being the project lifetime (in the simulation: 20 years).

HOMER also calculates the emissions of each system configuration and displays production as well as consumption parameters of each component. To test the robustness of the simulation, a sensitivity analysis is conducted. For this, the values of key variables have been altered and the effects on the overall system performance have been observed.

2.2. Data Acquisition

The sources for the input data are chosen carefully. If the sources state diverging values for certain parameters, the more conservative value has been chosen. HOMER requires different sets of input data and their sources for this case study are as follows [21]:

1. **Load profile:** The simulations are based on the electric and thermal demand of a hotel resort on Neil Island, India. Because most hotel clients require electric services between 18:00 h and 24:00 h, the electric demand is highest during this period of the day as depicted in Figure 1. Furthermore, using the occupation rate of the hotel rooms, the energy demand for hot showers and for air conditioning based on the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard [22] has been calculated. Based on historical data, the occupation rate has been assumed to be 70% during high season (from November to March) and 40% during low season (from April to October). The effect of the occupation rate on energy demand is reflected in Figure 3. For the whole year, the daily average electricity demand is 977 kWh and the average power demand is 40.7 kW.
2. **Meteorological data:** To calculate the global horizontal radiation falling on the location area, HOMER accesses the NASA surface meteorology and solar energy database [23] and then synthesizes hourly data from monthly averages. The synthesized solar data for the location with approximate latitude 11°59′ and longitude 92°7′ can be seen in Figure 2. The region offers good conditions for solar energy usage with relatively high average daily radiation of 4.72 kWh/(m^2·day) and an average clearness index of K = 0.482 (see Equation (3)).

3. **Equipment characteristics and Economic data:** To choose the parameters for each component, technical and economic data from commercially available products as well as values used in previous investigations are used.
4. **Technical data:** The maximum capacity shortage of the system has been determined to be 1%, which is a reasonably low value compared to the frequent electricity shortages of the reference case.
5. **Search space:** The search space was initially very broad (e.g., 10–500 kWe for the prime mover) and has been narrowed down iteratively to find optimal solutions.

To calculate the monthly average clearness index K, as shown in Figure 2, HOMER uses the following equation:

$$K = \frac{H_{ave}}{H_{o,ave}} \tag{3}$$

where H_{ave} is the monthly average radiation on the horizontal surface of the Earth and $H_{o,ave}$ (kWh/(m^2·day)) is the monthly extra-terrestrial horizontal radiation (kWh/(m^2·day)).

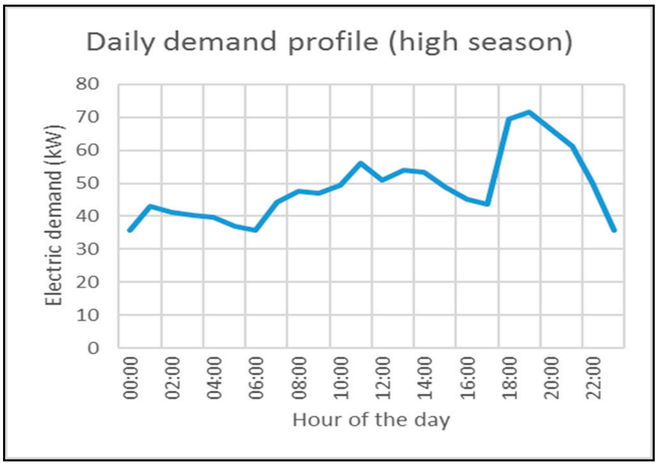

Figure 1. Electric load during high season for a representative day in January.

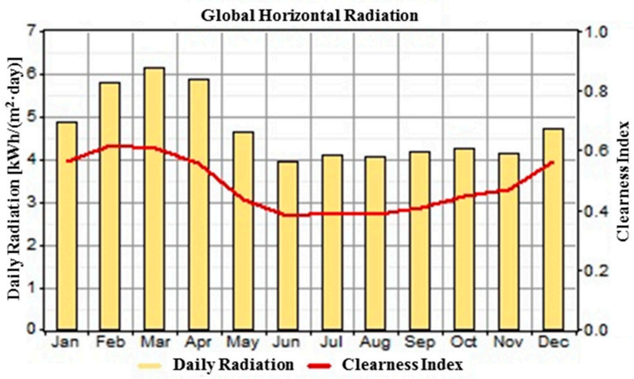

Figure 2. Global horizontal radiation and clearness index around the year.

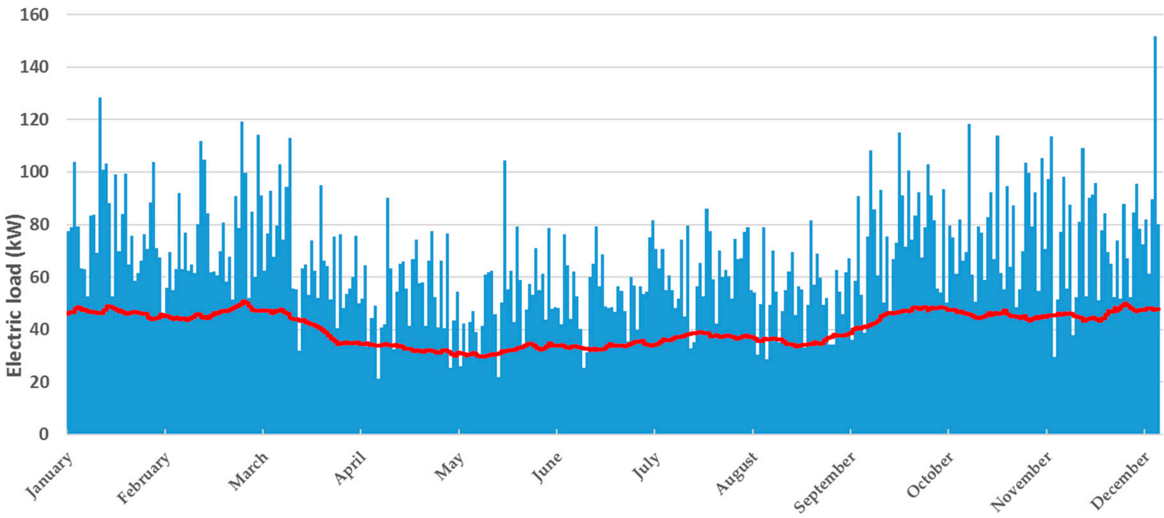

Figure 3. Max. electric load for each hour for the whole year in blue and 30-day average in red.

3. Case Description

3.1. Description of the Current Situation of the Island Grid and the Hotel

The Andaman Islands, located in the Gulf of Bengal, are inhabited by 380,000 people of which 85% live in rural areas. According to a report from the local administration, 90% of the energy generation was met by diesel generators in 2016 [24]. Of the 99.2 MW installed diesel generated capacity, diesel generators of 51.7 MW have outlived their life expectancy implicating increased malfunctions and maintenance issues. The use of diesel-generated energy is detrimental for the ecological balance of the pristine forests which cover 90% of the land mass of the Andaman and Nicobar islands. Additionally, the energy demand is growing rapidly due to a rising inflow of tourists. Therefore, several solar energy initiatives have been started or proposed, but the results have been poor so far [25]. On the case island, Neil Island, the currently installed diesel generators with a capacity of 0.6 MW are supplying electricity for more than 3000 people excluding tourists, but system breakdowns occur frequently. As a backup, many grid customers use small diesel generators in case of a grid outage.

The layout of the proposed hotel building blocks is shown in Figure 4. The hotel owner has shown interest to renovate his property completely. It has been assumed that the materials used for renovation of the buildings have similar properties to the previously used locally available materials. Each of the hotel guest blocks has a length of 25.65 m, a width of 10.0 m and a height of 4.9 m. Each block consists of a ground floor and a first floor with each floor containing five rooms, equalling a total of 40 rooms for all blocks. The rooms have a width of ca. 3.7 m, leaving enough space for an entrance and a staircase. The proposed block E consists of the reception, the restaurant and all other common facilities. A convenient location for a generator set and adjoining machines would be behind block C connected to the access road.

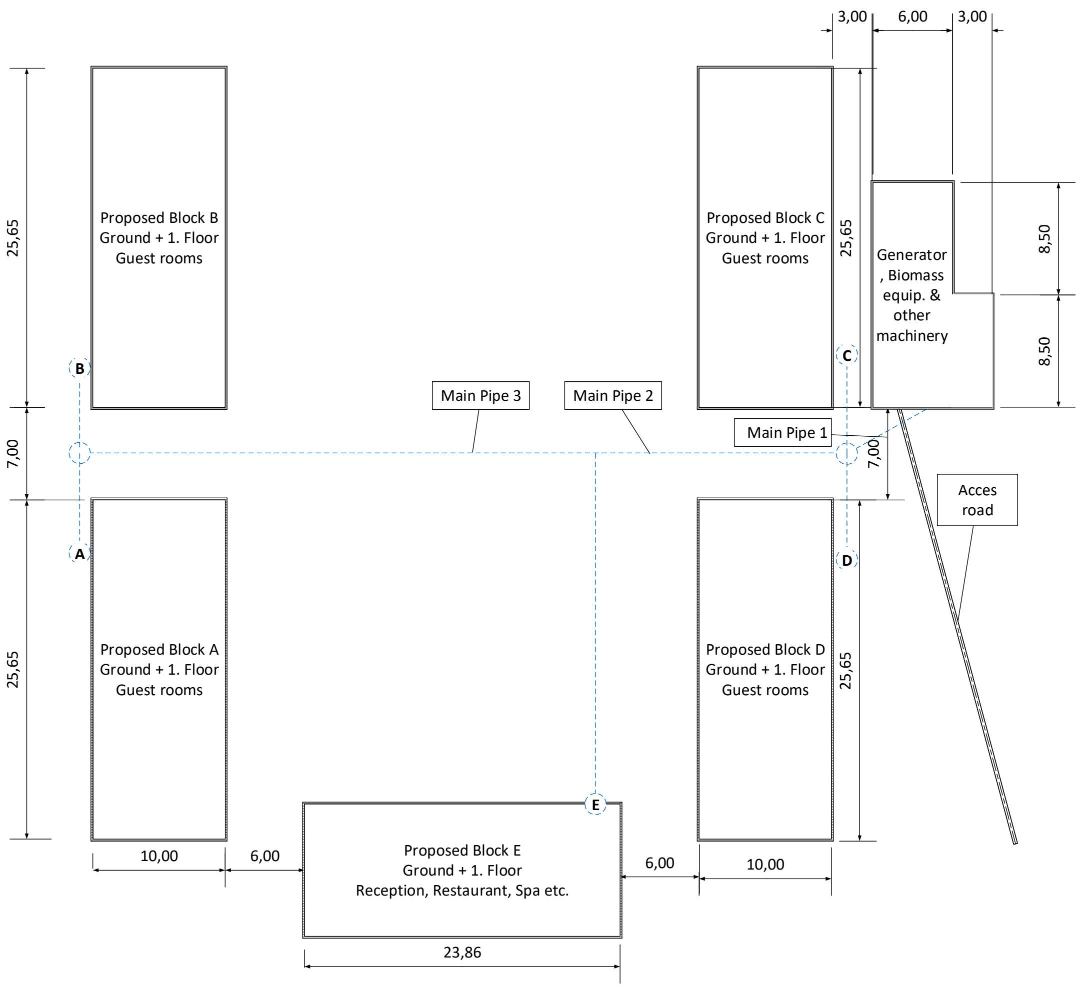

Figure 4. Layout of the proposed hotel building blocks.

3.2. Biomass Availability

Singal et al. [26] investigated the availability of biomass for gasification on the island and identified huge potential to optimize the use of agricultural waste. For example, each year more than 130 t of rice straw are fed to cattle, but another 94.5 t are just wasted without purpose. Similarly, more than 144 t of biomass waste from coconut and similar fruits are left on the fields. The minerals of the waste serve eventually as fertilizer after rotting on the fields, but they could be used for gasification beforehand. For a sustainable system, it is imperative to return the minerals. This can be done by converting the charcoal of the gasification process to fertilizer and hence to close the nutrition cycle. The estimated annual amount of unused biomass available on Neil Island is shown in Table 1.

Table 1. Annual potential for biomass gasification on Neil Island according to Singal et al. [26].

No.	Type of Biomass	Biomass Available for Gasification/year (kg)	Biomass Available for Gasification/year (kWh) [1]
1	Crop residues (rice straw)	94,550	274,284
2	Rice husk	54,690	190,604
3	Biomass waste (coconut shells, coconut husks etc.)	144,489	588,084
4	Biomass waste from bark and lops and tops on forest extraction from forest department	300,000	1,220,333
Σ	**Total**	593,729	2,273,306

[1] The energetic densities used for rice straw, rice husk, coconut shell and wood in kWh/kg are 2.91, 3.49, 4.07, and 4.07 respectively [26].

The syngas price per volume in USD/l, $C_{Syn,V}$, can be calculated using the following formula:

$$C_{Syn,V} = \frac{C_{Bio,E} \times w_{syn}}{\eta_{gasifier}} \tag{4}$$

where $C_{Bio,E}$ is the local biomass price in USD/kWh (value in the simulation: 1.25 Indian Rupees/kWh = 0.032 USD/kWh [26]), w_{syn} is the energy density of syngas in kWh/Nm^3 (value in the simulation: 6.5 MJ/Nm^3 = 1.8056 kWh/Nm^3 [27]) and $\eta_{gasifier}$ is the gasification efficiency (value in the simulation: 75% [27]). Using the formula a price of 3.009 INR/Nm^3 (about. 0.0463 USD/Nm^3) has been calculated and then further increased to 0.06 USD/Nm^3 to account for transport and biomass pre-treatment (e.g., for coconuts de-husking, de-shelling, de-pairing) costs.

3.3. Description of the Cases:

Four cases have been modelled in HOMER:

1. **Base Case:** The diesel base case represents the currently used conventional diesel-based system. The owner receives electricity from the island grid and uses a 160 kW diesel generator as a back-up during the frequent electric outages to meet electricity demands of up to 152 kW (see peak value in Figure 3).
2. **Solar-assistance Case:** The diesel generator is supported by PV panels and batteries. For this case, a practical limitation of mounting PV panels only on the roof area has been ignored.
3. **Bio-solar Case:** A gas engine fuelled with syngas from a gasifier substitutes the diesel engine. The gas engine is also supported by PV panels and batteries. The PV panel size does not exceed the available rooftop area. The system works entirely off-grid.
4. **Bio-Solar CCHP Case:** The same system configuration as in Case 3 is applied. However, a thermal load is introduced to ensure continuous operation of an absorption chiller (AC) which relieves the electrically driven vapour compression chiller (VC). In case the gas engine is turned off, a boiler provides the necessary heat energy by burning syngas.

To calculate the area needed for the PV panels A_{pv} the following equation has been used:

$$A_{pv} = \frac{P}{\eta_{pv} \times E_{ter}} \tag{5}$$

where E_{ter} is the max. irradiance (in the simulation a value of 1 kW/m^2 is assumed [28]), η_{pv} is the efficiency of the PV panel, and P is the output power of the PV panels [kW].

The system configurations of the four cases modelled in HOMER are shown in Figures 5–8. A more elaborate scheme of the CCHP configuration is illustrated in Figure 9.

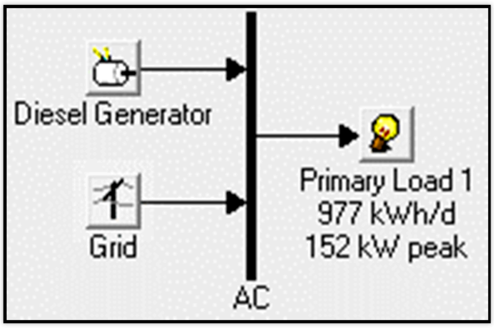

Figure 5. HOMER schematic of the base case 1.

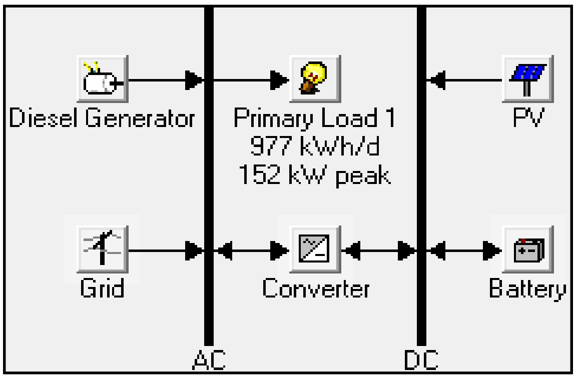

Figure 6. HOMER schematic of the solar-assisted diesel engine case 2.

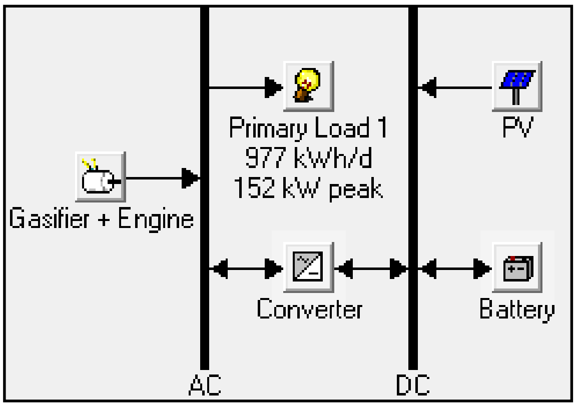

Figure 7. HOMER schematic of the biomass-based, solar-assisted case 3.

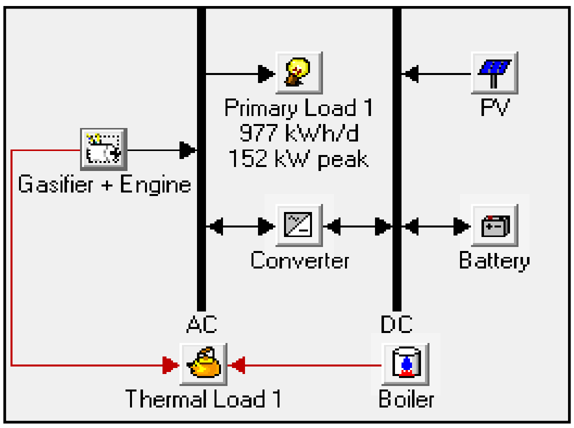

Figure 8. HOMER schematic of the biomass-based, solar-assisted CCHP case 4.

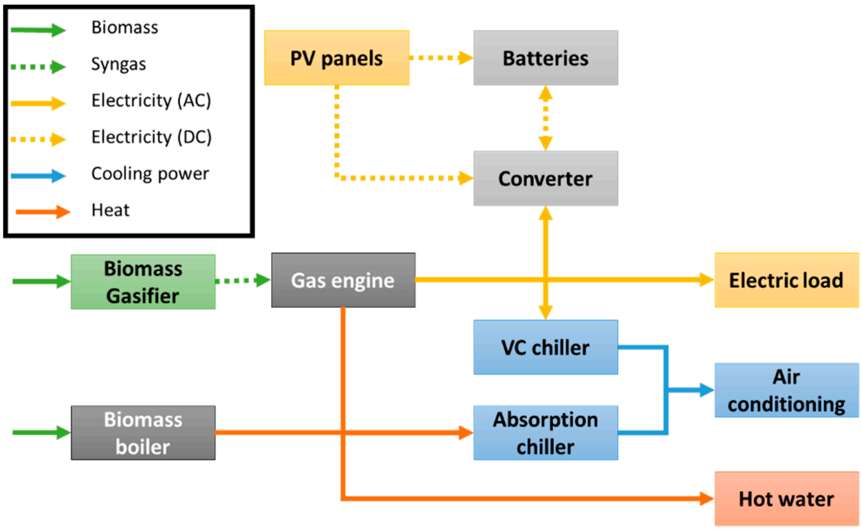

Figure 9. Elaborated schematic of the CCHP system, Case 4.

3.4. Description of the Components

For all the component prices modelled in the system, commercial or scientific sources have been used for cost assumptions. For price ranges, the most conservative price estimation has been chosen and 15% have been added to each component price to account for shipment and engineering costs. In some cases, higher prices have been assumed due to building design requirements. A summary of the components input data is shown in Table 2.

Table 2. Summary of the component input data.

Component	Capital & Replacement Cost	O&M Cost	Further Characteristics
PV panels	1000 USD/kW and 1000 USD/kW [29]	25 USD/year/kW [30]	Lifetime: 25 years Derating factor: 80% Slope: 12° Max. Efficiency: 15%
Batteries	1500 USD/kW and 1500 USD/kW [31]	30USD/year/battery [31]	Model: Surrette 4-KS-25PS (1900Ah, 4 V Deep) Cycle Battery [31] Lead-acid type Minimum battery lifetime: 7 years Lifetime Throughput: 10,973 kWh 6 batteries per String (24 V String)
Gasifier + Gas engine	3000 USD/kW and 3000 USD/kW	0.03USD/kWh [32]	Lifetime of both: 15,000 h [33] Gasifier efficiency: 75% [27] Engine max. efficiency: 24% [34]
CCHP measures	25,850 USDfor entire equipment	0.013USD/kWh [32]	75 kW Heat exchanger 42 kW AC (*COP*: 0.6) [35] Capital cost include piping, engineering and shipment 20 year lifetime
Converter	750 USD/kW and 750 USD/kW [36]	10USD/year/kW [30]	Lifetime: 20 years, Inverter efficiency: 90% Rectifier efficiency 90%
Diesel engine	600 USD/kW and 600 USD/kW [36]	0.02 USD/kWh [36]	Lifetime: 20,000 h Minimum load: 40% [37] Maximum efficiency: 38% [37] Emission data from HOMER Forced on from 18.00–24.00 every day

3.4.1. Biomass Pre-Treatment and Gasifier

Due to fuel requirements of the gas engine, a down-draft gasifier has been chosen which produces high quality gas with low tar content compared to up-draft or cross-draft gasifiers [11]. Small-scale downdraft gasification systems with 20 kWe are commercially available for less than 2000 USD/kWe [38] and Bocci et al. [39] state that the price for small-scale cogeneration systems can even be as low as 500 USD/kWe for systems with less than 1000 kWe. Any necessary expenditures for equipment for pre-treatment (e.g., de-husking machines) and for post-treatment (e.g., filter, scrapper, vortex cylinder, etc.) are included in the capital costs. In the simulation, the engine is designed for net electricity generation; therefore, any power needed for gasification is included in costs and calculations. Due to the lower fuel quality of the syngas, the maximum efficiency of the gas engine has been de-rated by more than 30% compared to that of a diesel engine [34].

3.4.2. Exhaust Heat Usage and Absorption Chiller

All of the systems are designed to serve primarily the electricity demand. When the engine does not operate and hence does not produce enough thermal heat, a boiler fuelled with syngas will provide the missing thermal energy needed. On the one hand, the recovered heat can be used to replace the electric air-source heat pumps for hot shower water. These heat pumps are currently used to provide hot water for the hotel guests. They would be entirely replaced for Case 4. The equation for electric energy saved for heating $E_{s,h}$ is:

$$E_{s,h} = \frac{Q_h}{COP_{elec,h}} \tag{6}$$

where Q_h is the heat used for heating and $COP_{elec,h}$ is the coefficient of performance (COP) of the electric air-source heat pumps.

On the other hand, the recovered heat can fuel a heat-driven AC to relieve the currently used VC. The equation to calculate the electric energy saved for cooling $E_{s,c}$ is:

$$E_{s,c} = \frac{Q_c \times COP_{\mathrm{AC}}}{COP_{\mathrm{VC}}} \tag{7}$$

where Q_c is the heat used for cooling, COP_{AC} is the COP of the AC and COP_{VC} is the COP of the electricity-driven VC. The total electric energy savings $E_{s,total}$ are calculated with:

$$E_{s,total} = (E_{s,c} + E_{s,h}) \times f_{M\&R} \times f_{losses} \tag{8}$$

where $f_{M\&R}$ is a factor variable to account for maintenance and repair intervals and f_{losses} is a factor variable to account for heat losses due to tubing. Q_h and Q_c may either be supplied as exhaust heat from the engine or as direct combustion heat from the biomass boiler in case the engine is turned off.

The biomass boiler allows shutting down the engine so that no excess electricity is produced and the engine lifetime is increased. However, in some occasions it may be much more efficient to generate electricity for the electric chillers instead of heat for the AC. This is a suboptimal cooling control lowering the total system efficiency. Consequently, the system costs will be higher than under an optimal control strategy.

Key technical and economic input data for the CCHP measures are summarized in Tables 3 and 4. Using the data in Table 3 and Equations (6)–(8), $E_{s,h}$ amounts to 48 kWh per day equivalent to 5% of the average daily electricity demand and $E_{s,c}$ amounts to 288 kWh per day equivalent to more than 29% of the average daily electricity demand. $E_{s,total}$ amounts to 244 kWh equivalent to 25% of the average daily electricity demand.

Table 3. Technical input data for CCHP measures.

Variable	Variable Value
Heat recovery rate of the engine waste heat (based on [40]):	70%
Hourly heat used for heating: $Q_{ex,h}$	5 kWh
Hourly heat used for cooling: $Q_{ex,c}$	70 kWh
Average *COP* of electric air-source heat pumps: $COP_{elec,h}$ (based on [41])	2.5
Average *COP* of AC: COP_{AC} (based on [10])	0.6
Average *COP* of VC: COP_{VC} (based on [15])	3.5
Factor variable for heat losses: f_{losses}. (author's judgement)	0.9
Factor variable for maintenance and repair intervals: $f_{M\&R}$ (based on [42,43])	0.81
Thermal efficiency of the boiler before distribution [44]:	0.9

Table 4. Economic input data for CCHP measures.

Variable	Variable Value
Price for AC equipment [32]	50 USD/kW effective cooling power
Price for heat exchanger equipment [32]	50 USD/kW effective heat recovery
O&M costs for heat exchanger [32]	0.005 USD/kWh
O&M costs for AC [32]	0.008 USD/kWh
Additional costs for tubing based on architectural calculations	10,000 USD
Additional costs for engineering, shipment etc.	10,000 USD

4. Results

The configurations optimized according to the NPC for each case are shown in Table 5. In Case 2, the area available for PV panels has not been limited, while in Cases 3 and 4 the maximum rooftop area of 600 m^2 with a nominal peak value of 85 kW for the PV panels has been taken into account according to Equation (5).

Table 5. Optimal system configurations for Cases 1–4.

Component	Case 1 (Diesel-Grid)	Case 2 (Solar-Assisted)	Case 3 (Bio-Solar)	Case 4 (Bio-Solar CCHP)
Diesel generator	160 kW	90 kW	-	-
Gasifier + Gas engine	-	-	50 kW	40 kW
PV panels	-	200 kW	85 kW	85 kW
Batteries (Nom. Capacity)	-	42 kW in 7 strings (319 kWh)	84 kW in 14 strings (638 kWh)	48 kW in 8 strings (365 kWh)
Converter	-	60 kW	50 kW	45 kW
Boiler	-	-	-	75 kW

4.1. Economic

The simulation results show that the base case would be the most expensive solution for the hotel owner with a NPC of 1,956,700 USD as illustrated in Figure 10. Case 3 would save the owner more than 326,000 USD over 20 years, while Cases 2 and 4 would save him more than 500,000 USD each. However, the capital investment costs of 96,000 USD, which are necessary for replacing the old diesel generator, are substantially lower than the costs for engineering, shipping and installing any of the system configurations proposed in cases 2, 3 and 4, which all require more than 300,000 USD of capital investment. The payback periods for cases two, three and four are five years, seven years, and four years, respectively.

A more detailed view of the cash flow for case 4 is shown in Figure 11. The costs for the gasifier and the gas engine comprise more than 50% of the total NPC. Additionally, it shows that, within these costs, the expenditure for replacement and fuel make up the two major assets.

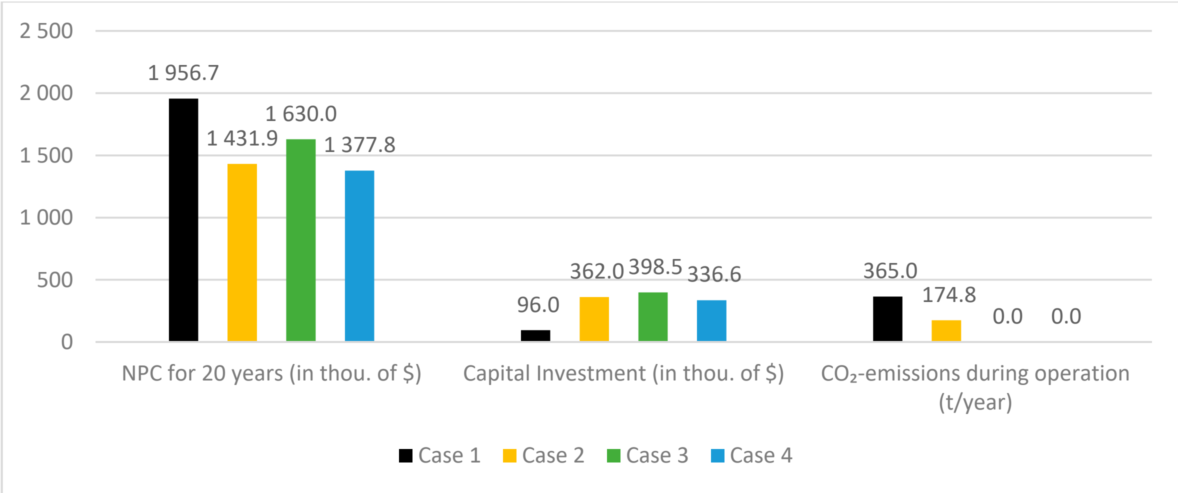

Figure 10. Comparison of NPC, capital investment, and CO_2 emissions for all four cases.

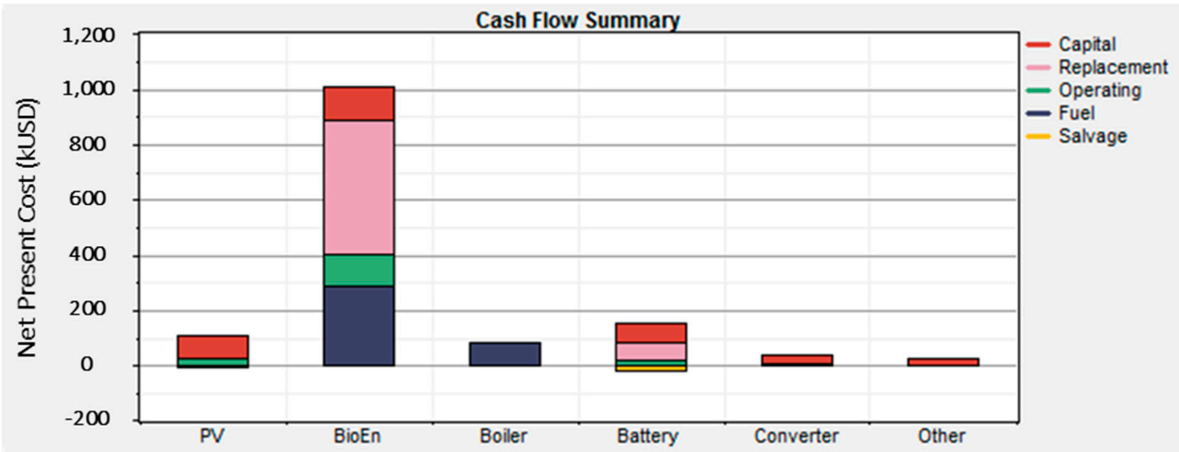

Figure 11. Detailed cash flow summary for Case 4.

4.2. Energetic

The fuel consumption and electricity generation of the system components are shown in Table 6. In the base-case, 59% of the electricity is provided by the grid and the remainder is generated by the diesel engine with a diesel consumption of 490,511 kWh/year or 49,849 litres/year. The PV panels supply 58% of the electricity in Case 2 and lower the grid purchases significantly. However, the diesel consumption is still 384,817 kWh/year or 39,107 litres/year. The mean electrical efficiencies of the engine are 33.1% in case 1 and 35% in Case 2. This implies that in Case 2 the engine is operating for less time, but when it is operating, it is working more efficiently. One reason for this might be that the batteries satisfy the electricity demand for lower loads. The PV panels mostly reduce the grid purchases (from 59% down to 15%). The biomass consumption in Case 3 is 1,526,573 kWh/year, which equals 67.2% of the biomass available on the island (see Table 1). The efficiency measures in Case 4 would lower this value to 1,142,813 kWh/year or 50.3%. In Cases 3 and 4, the syngas engine has a mean electrical efficiency of 24.1% and 22.7%, respectively. The difference in engine efficiency between Cases 3 and 4 may be caused again by the batteries, because in Case 3 the greater battery capacity can supply electricity more often, where otherwise the engine would run in a lower partial load mode. Including the gasification efficiency of 75%, this leads to system electrical efficiencies of 18.1% for Case 3 and 17.0% for Case 4, which are considerably lower than the efficiencies of Cases 1 and 2. However, in Cases 1 and 2 the losses due to oil processing, as well as longer transport chains, are not included in the efficiency calculation.

The mean total efficiency of the engine in Case 4 is 80.6% and the global efficiency of the entire CCHP system, including the gasifier subsystem, is 60.5%. Interestingly, using more thermal energy of the engine and, hence, saving electric energy demand, lowers the percentage amount of electricity generated by the gas engine and raises the percentage of solar energy. This may be partly because of the downscaling of the syngas engine.

Table 6. Consumption and generation of the sub-systems.

Sub-System	Case 1 (Diesel-Grid)	Case 2 (Solar-Assisted)	Case 3 (Bio-Solar)	Case 4 (Bio-Solar CCHP)
Diesel consumption	490,511 kWh/year	384,817 kWh/year	-	-
Biomass consumption	-	-	1,526,573 kWh/year	1,142,813 kWh/year
PV generation	-	281,986 kWh/year 58%	119,832 kWh/year 30%	119,832 kWh/year 38%
Diesel engine generation	162,281 kWh/year 41%	134,741 kWh/year 28%	-	-
Gas engine generation	-	-	276,372 kWh/year 70%	194,756 kWh/year 62%
Grid purchases	233,729 kWh/year 59%	71,825 kWh/year 15%	-	-

4.3. Ecological

The diesel-based system emits 365 t of CO_2/year, which is equivalent to the amount of CO_2 emitted by more than 57 Europeans or 214 Indians [45]. The solar and battery extensions in Case 2 lower the emissions to 174,800 kg CO_2/year, while in Cases 3 and 4 the CO_2 emissions have been considered as negligible due to the biomass regrowth cycle. However, these calculations do not include any emissions caused by diesel or biomass transport to the energy system, nor does it include the energy required for material extraction and construction of system components. A life cycle assessment of the energy sources including the energy incorporated in constructing and transporting the system components would give a clearer picture of the overall ecological impact. Furthermore, additional GHG effects from Nitrogen Oxides (NOx), particulate matter or sulphuric oxides have not been analysed within the simulation. However, the NOx emissions are probably lower in Cases 3 and 4 than in Cases 1 and 2 due to lower combustion temperatures [46]. It must also be noted that the gasifier system poses a significant health risk for humans as well as animals due to the high carbon monoxide proportion of the syngas. This risk must be mitigated through proper installation and security precautions.

4.4. Sensitivity Analysis

A sensitivity analysis has been conducted to test the robustness of the simulations, as there are inevitably uncertainties within the assumptions. These are on the one hand due to incomplete or unavailable data (e.g., for the precise biomass price from each individual farmer) and, on the other hand, due to volatilities of variables over time (e.g., volatility of oil price). As shown in Figure 11, the replacement cost for the gasifier and the gas engine, as well as the fuel costs, have the strongest impacts on the NPC in Case 4. Therefore, these values were altered in the sensitivity analysis and the changes in NPC due to the alteration were simulated. Figure 12 shows how the NPC of the overall system is affected by increasing or decreasing the fuel price by 50%. The optimal system configuration for the original price (of 100%) was kept. A change in the diesel price has a stronger impact on the NPC in Cases 1 and 2 than a change in the biomass price on the NPC in Cases 3 and 4. It should be noted that the NPC of the CCHP system in Case 4 with a biomass price of 150% would still be 20,300 USD or 1.3% lower than the NPC of the conventional system with a diesel price lowered to 50%.

This highlights the robustness of the system even with extreme price changes. It is also remarkable that the Case 2 system with a 50% diesel price would outperform any other system. The effects of a change in generator lifetimes on the overall system NPC are illustrated in Figure 13. In cases 1 and 2, the effects are marginal, mostly due to the low generator replacement costs. In Cases 3 and 4, however, changing the lifetime of the gasifier and the gas engine strongly changes the NPC of the overall system. For example, in Case 3, a 50% shorter generator lifetime (7500 h) leads to higher replacement costs of more than 732,000 USD, or 44.9% compared to the NPC of the system with the original lifetime of 15,000 h.

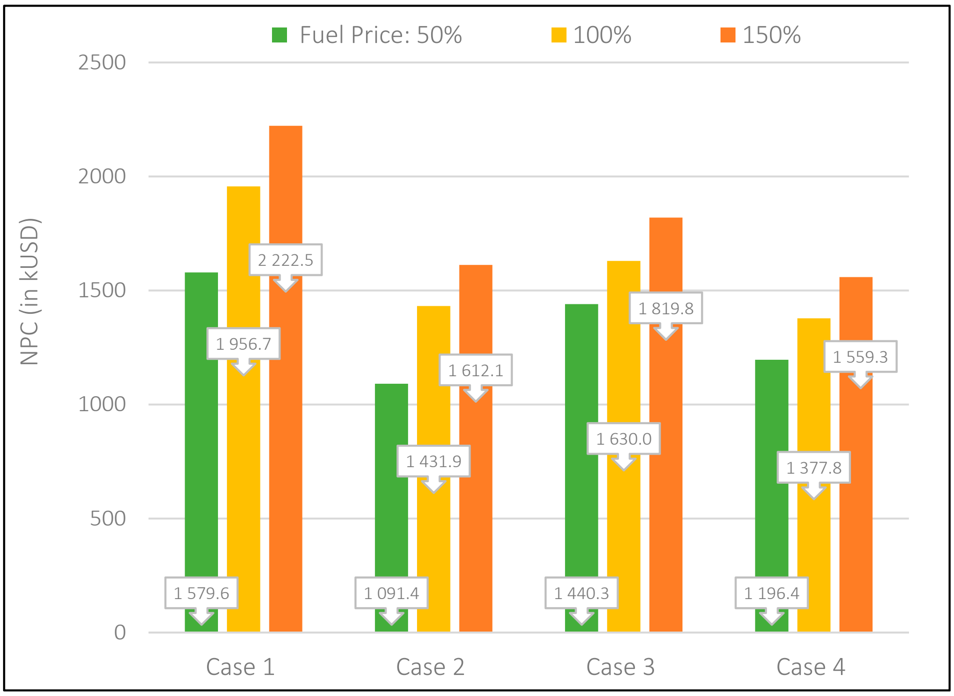

Figure 12. NPC for all four cases with different fuel prices. Note: For Cases 1 and 2 the diesel price was altered, while for Cases 3 and 4 the syngas price was altered.

5. Discussion

Despite very conservative assumptions, the results indicate an economic and ecological superiority of the biomass-based CCHP system in comparison with a conventional diesel-based grid solution for the specific case study on the island. The system could even perform better if the cooling control system would be further optimized, as a simplified model has been used in the simulation. The savings of more than 578,000 USD over 20 years and a considerably short payback period of four years could facilitate attracting private investment funding to counter the comparatively high investment costs. Additionally, the ecological benefits in combination with the willingness of the Indian government to subsidise such systems could lower the remaining investment funding necessary [12]. The sensitivity analysis shows that the benefits of Case 4 are not just robust towards fuel price changes but also that the smart and renewable CCHP system outperforms the conventional fossil-fuelled system in every scenario depicted. However, any shortening of the gasifier system's lifetime endangers its economic viability. It is, therefore, crucial to design the system as flawlessly as possible.

Remarkably, if an unshaded area for enough PV panels would be available, the system in Case 2 would achieve nearly equal economic viability as the system of Case 4, without the complexity of a biomass-based CCHP system. Furthermore, the system configuration of Case 2 is more robust towards generator lifetime changes due to the low costs of diesel ICEs. The capital investment costs of PV panels as well as of batteries are predicted to further decrease in the coming years, which would, in turn, further improve the economic viability of such systems [47,48]. However, the volatility of oil prices could lead to financial problems for a diesel-driven system, while a biomass-based solution could be fixed to local and more stable biomass supply contracts. In addition, the CO_2 emissions would still be high due to the diesel and grid emissions, which might complicate the process of winning government support.

Case 3 is economically outperformed by Case 4 in every scenario and in all but one scenario by Case 2. If the generator lifetime is 50% shorter than assumed, Case 3 would even be economically inferior to the base case. This can be partly attributed to the low system efficiency of just 18.1% due to the losses in the gasifier system and the engine efficiency reduction due to the fuel's lower quality. This highlights again the importance of an optimal system configuration for any biomass-based solution, but also underlines the economic advantages of the CCHP extensions. Apart from the low capital investment costs, the conventional diesel-based system of Case 1 also offers the simplest and, hence, most convenient solution, because replacing the diesel engine requires the least engineering and design work. Additionally, the system of Case 1 would also require the least educational training for operation and maintenance of the system. Nonetheless, the economic and ecological drawbacks are strong arguments to put an effort into the renewable energy solutions.

A practical realization similar to the system proposed in Case 4 is under investigation with project participants from academia, industry, and politics. Future research should further support the implementation of such a system as well as measure the discrepancies between the real system and the simulations. Adjacent to system-specific examination, socioecological considerations of a broader context should be included in a future business plan for any such system. Possibilities to buy the biomass from local farmers on fair terms and to transport it to the system location have to be further studied. During the gasification process bio char and ash is produced. To close the biomass cycle, the viability of transforming the bio char to fertilizer with the aim of selling it to the local farmers has been considered. The individual benefits of the proposed biomass-fired, solar-assisted CCHP system for various interest groups on the island are summarized in Figure 14.

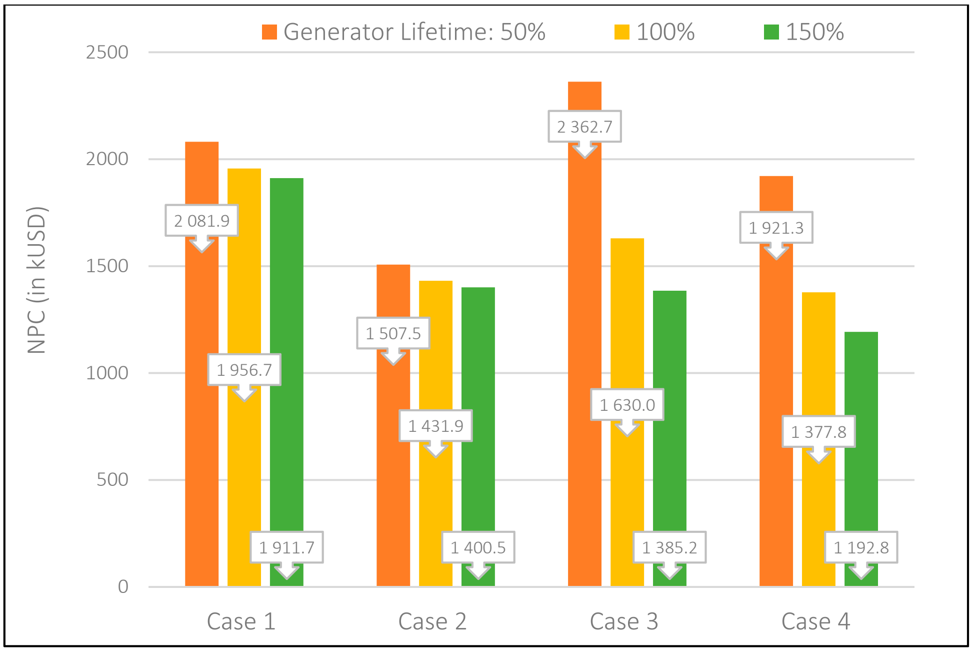

Figure 13. NPC for all four cases with different generator lifetimes.

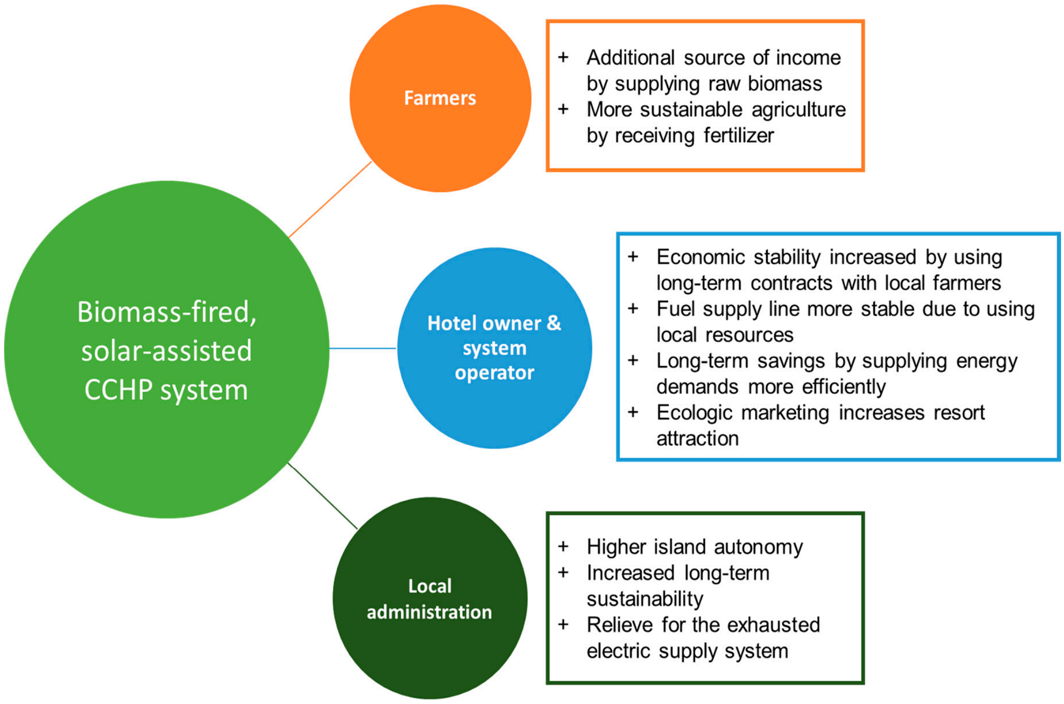

Figure 14. Benefits of a smart CCHP system for various interest groups of the Andaman Islands.

6. Conclusions

Based on historical demand data, commercial info and scientific literature of four cases were investigated to satisfy the energy demand of a hotel resort on Neil Island, India. The results show that a biomass-based, solar-assisted CCHP solution outperforms the grid-connected diesel-based system, not just ecologically but also economically. More precisely, the biomass-based CCHP solution compared to the conventional system leads to savings of more than 578,000 USD over a period of 20 years and would pay off within less than four years. Additionally, 365 t of CO_2/year are saved. Fuel price and generator lifetime have been identified as key variables for the economic performance of the system and the robustness of each system has been tested in a sensitivity analysis. Using the biomass system just for electricity generation and not applying CCHP measures considerably decreases the potential of the system. Economic results similar to those of the biomass-based, solar-assisted CCHP could be achieved by supporting a smaller diesel-generator with additional PV panels and batteries. Additionally, this case proves to be more robust towards changes in the assumed generator lifetime. However, there would still be significant CO_2 emissions due to diesel combustion. In addition, a significantly larger unshaded area would be needed for the PV panels, which is currently not available at the proposed system location. Apart from the technological, the socioeconomic benefits of the system have also been discussed.

This study indicates enormous ecological and economic potential of a biomass-based energy system for a specific case on a specific island. These findings can also be applied to similar cases of remote islands and areas, where high fuel prices and non-continuous supply of fuel hinder socioeconomic development. Future studies could include investigations on additional extensions of the system with other energy services (e.g., potable water, biofuels) and the impact of such a system on the socioeconomics as well as on the ecological environment of the island.

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Nomenclature

3E	Economic, Energetic, and Ecological
AC	Absorption chiller
CCHP/Trigeneration	Combined Cooling, Heat, and Power
CHP	Combined Heat and Power
COP	Coefficient of Performance
GHG	Green House Gases
HOMER	Hybrid Optimization of Multiple Energy Resources
ICE	Internal Combustion Engine
NOx	Nitrogen Oxides
NPC	Net Present Cost
O&M	Operation and Management
ORC	Organic Rankine Cycle
PV	Photovoltaic
VC	Vapour compression chiller

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