Hybrid Renewable Power Systems for Generation of Own Power by Small and Medium-Scale Enterprises

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Abstract. Decentralized power generation, from renewables, is an attractive option for the future energy transition. Through a case study, the techno-economic feasibility to produce own power from distributed renewable to de-carbonize the operations of the Small and Medium Scale Enterprises (SMEs) was critically analysed. The case study was performed on one of the leading printing outfits of Sri Lanka. Solar photovoltaic (PV) and biomass gasification systems are the most cost-efficient and easy to operate technologies for grid-connected, small-scale power generation, at present, for the context. Grid integration has been found as a major challenge, in both technical and economic parameters of the project. The low capacity factor of solar PV and complexity of the supply chain for biomass power systems are critical to the respective technologies. A hybrid Solar PV-Biomass gasification power plant would have superior techno-economic performances with lower environmental impact than stand-alone systems. An equal share of the net power capacity between the technologies was obtained as the most suitable combination for the proposed hybrid power plant. A net carbon dioxide reduction of more than eighty percent of the operations of the SMEs is feasible. Socio-political factors also have a high impact on overall viability of such small-scale systems.

1 Introduction

Technological progress, along with human development is leading to an increasing consumption and demand of energy [1]. Besides, unplanned growth, together with the unregulated use of fossil fuels has resulted in significant acceleration of climate and environmental degradations observed and described by the scientific community [2]. From the consumption point of view, industries accounted for 42% of the world final energy consumption in 2015 [4]. Small and Medium scale enterprises (SMEs), comprising most of the industrial sector [5], especially in the developing countries, accounts for a high share of the total industrial energy consumption. Apart from energy efficiency measures, own

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energy generation from renewables forms an innovative strategy to decrease the carbon footprint of operations of such industries.

Power generation from renewables is a major instrument towards promoting the production of clean energy and tackling climate change. Distributed power generation, due to multiple advantages, will play a crucial role in this transformation, besides centralized power systems, [7]. However, technological challenges and cost-competitiveness of renewable energy-based power production, both with respect to grid integrated and off-grid systems, are major challenges, especially in developing countries. Lack of adequate technical knowledge, especially for the development of small-scale power generation systems often lead to poor system design resulting in economic failure. A strong technological framework and support, together with national and international financial strategies like subsidies, public funds and innovative policies are crucial as well for the development of distributed renewable power generation units.

However, generation of own green power has its own drawbacks. Often the SMEs would lack adequate technical knowledge for selection and design of such systems. Over-simplified evaluations based on economic assessments, though often attractive, include inappropriate assumptions, resulting in poor system design and economic failure of such systems. Besides SMEs are usually located either within urban areas or have inadequate space within their premises, presenting considerable barriers to set up such power generation units on site.

Thus, in the present case study, the techno-economic feasibility of an offsite, small-scale grid integrated renewable power generation system for own energy needs by SMEs was studied considering multiple perspectives technology availability, economic feasibility, as well as social, environmental and policy implications.

2 The Case Study

The necessary evaluations were performed through a case study. Accordingly, a leading newspaper company in Sri Lanka, representing a typical SME, was selected to evaluate the feasibility of a small-scale grid-connected renewable power plant to decarbonize its operations. The use of electricity for printing and the presence of fossil-derived power plants in the electricity mix of Sri Lanka [6] results in inherent carbon emissions from printing operations. The annual electricity consumption was estimated as 5.2 GWh.

The newspaper printing facility is in a largely urbanized location near Colombo, Sri Lanka. An off-site grid integrated power generation system was therefore considered to be analysed. Due to high land prices and local land acquiring policies, around 40.5 hectares (ha) of land in Bingiriya, in the North-Western Province of Sri Lanka, 120 km distance from the printing facility was identified as suitable. The rural area is in the coconut belt, within the dry zone of Sri Lanka.

The available land comprises a tank, 12.2 ha of paddy fields and around 28.3 ha of coconut plantations. The river Deduru flows within 1000 metres from the land. However, an upstream dam results in the river to run dry most of the year, raising water constraint issues for the project. Other analyses of roads, infrastructure, site vegetation, soil condition, surrounding locality including cultural and environmental aspects were conducted for the overall feasibility of a renewable energy project development.

2.1 Assumptions

Several rational assumptions were made including a conservative evaluation approach. Especially, for a biomass power generation unit, a well-designed and maintained biomass-based power generation unit can achieve around and above 70% capacity factor for

yearlong operations [7]. However, a capacity factor of 60% for the present evaluations was considered along with inferior overall system efficiency of 20%.

Besides technological feasibility assessment, capital expenditures (CAPEX), operation expenditures (OPEX), project internal rate of return (IRR), payback period and net present value (NPV) were evaluated. Project lifetime of 20 years was assumed. A debt-equity ratio of 70:30 was selected for financial evaluations. Grid balancing fees and carbon credits were not considered based on local laws. Only locally available and technologically matured solutions were considered for system design due to ease of project implementation and operation. Detailed economic parameters were assumed based on the local Sri Lankan policies as follows:

Corporate tax: 10%; Capital insurance rate: 0.50%; Decommissioning factor: 5%; Inflation rate in Sri Lanka: 9.72%; Cost of Equity 16%; Tax holiday period: 6 years [8]. Cost of Biomass Feedstock: 40 $/tonne

Considering limitations of SMEs, capital expenditure (CAPEX) was limited to 3 million $ considering a small-scale project. A payback period of around five years with a project internal rate of return (IRR) of over 10% was considered for the economic feasibility of such small-scale projects.

3 The Case Study

3.1 Grid Connection

Grid connection, especially for fluctuating renewables presents technical challenges [9]. The nearest 132/33 kV Grid Substation, being 30 km distance away, a severe grid integration challenge was faced. The necessary infrastructure of a dedicated medium voltage line would cost an estimated 0.6 million $ severely affecting the economic viability of the small power generation system.

A 33KV Medium Voltage feeder was assessed to be feasible for grid connection based on the carrying capacity of the feeder. A 33KV feeder, connecting two substations, around one kilometre from the selected land was identified to a have a feed-in capacity of 3MW. The absence of power generation units connected to the feeder would allow the grid integration of the proposed unit at a cost of nearly fifty times less, at around 12000 $. However, with an increase in distributed power generation units, grid integration will become a major techno-economic challenge for a small-scale grid-connected power generation unit.

3.2 Resource Feasibility and System Design

Solar, wind and biomass-based power generation are the most mature forms of renewable power generation for small to medium scale applications.

3.2.1 Wind

On-shore wind turbines are currently the most economical option for harnessing wind energy on a small scale. Even though Sri Lanka has an excellent wind potential, the identified site is in an area with poor or marginal wind potential [10] . Additionally, the selected land is surrounded by coconut plantations. Being over 10m high, this would severely impact the performance of wind turbines. Besides, the area is frequented by

migratory birds, presenting significant social and environmental negativities towards developing a wind farm. Unfavourable resource, high land requirement, together with a lower plant factor would limit small-scale wind power units.

3.2.2 Solar

Among different technologies to harness solar energy, solar photovoltaics is one of the most promising and fastest growing industries worldwide [11]. The yearly average solar insolation was estimated at around 1600-1700 kWh/m2 with a yearly mean daily average ambient daytime temperature ranging from 24-30 ºC at the selected location. A solar PV generation system was therefore technologically viable.

A 4MW standalone solar PV power plant with an average annual capacity factor of 17.5% would be necessary to produce 5.2 GWh annual energy. The net land requirement would be around 80 ha.

However, as discussed, the grid connection feasibility is limited to 3MW without major economic constraints for the selected case study. Hence a stand-alone 3MW solar PV power plant would fail to meet the necessary generation requirements of 5.2 GWh per year for the printing operations.

3.2.3 Biomass

Even though medium to large scale biomass to power is a matured technology, the technology development issues remain regarding small power plants (around the order of 1 MW) [7].

The primary limitation to the development of biomass power plant is the availability of resources, namely raw biomass and water. Any capacities over 2MW, as studied, would require extensive resource management, or over-dependence on external supplies, often leading to unwanted complicacy of operations of small-scale projects. Gasification-based systems are preferable for small-scale operations. Modular, engine-based gasification units were found to be the most suitable technology for small-scale biomass to electricity applications. Besides requiring less space with lower water consumption, the presence of internal combustion engines results in a more robust system with higher part load efficiencies [12].

Studied feedstocks included energy crops and agricultural wastes. Co-cultivation of dendro (Gliricidia sepium) and coconut was obtained as the optimum solution for establishing a dedicated supply chain for the proposed biomass power plant in Sri Lanka. Along with dendro, an energy crop, coconut wastes, including shells and husks was considered as the primary feedstock. Based on local studies conducted by the authors, a mixture of 39% by weight coconut wastes and 61% by weight of dendro is feasible to be obtained through co-cultivation. A considerable LHV of 16 MJ/kg of the mixture (20% moisture) would result [13]. Availability of raw material from within the material flow of the SMEs was considered as a valuable resource. Waste paper, currently sold for recycling was found as an economically feasible resource from within the printing facility, securing the supply chain further.

Segregated solid fractions of municipal solid wastes (MSW) as an alternative raw material was considered. However, technological and social challenges with regards to collection, sorting and gasification of MSW would render MSW unsuitable as a feed-stock.

A 1MW stand-alone biomass gasification unit, running at 60% capacity factor, would be able to produce the required yearly energy of 5.2 GWh necessary for printing operations.

For such a unit, a feed rate of 24 tonnes/day, would require around 202 ha of dendro-coconut co-cultivated lands. Cost of feedstock would be 40 $ per tonne of mixed dendro-coconut waste feed. 1200 tons of waste paper was identified to be available annually from the newspaper printing facility as waste from printing operations. This would substitute around 20% of the dendro-coconut waste requirement for a 1MW system. The net cost of waste paper, including transportation charges from the printing facility to the biomass power plant, was estimated to be 0.5 Sri Lankan Rupees (LKR)/kg of paper, considerably decreasing the economic burden of the cost of feedstock on the biomass power plant.

An economically optimized strategy to develop dedicated farming and bulk procurement will play a crucial role in the viability and higher capacity operations of the proposed power plant.

3.2.4 Hybrid Power Generation

Power generation systems from multiple energy sources have significant advantages over those from the single energy source.

Small-scale grid-connected wind energy generation, being obtained both techno-economically challenging, was not considered for a hybrid system design. However, a solar-biomass based hybrid system was found to be technologically feasible in the present case study. Hybridization of the solar photovoltaic plant with the biomass-based power generation unit has been shown to complement each other to produce a stable power overcoming individual drawbacks [14]. Multiple combinations of hybridization based on individual system size were studied, that would be able to supply the required minimum output of 5.2 GWh of annual energy.

Different hybrid systems capacities combining the solar PV and Biomass gasification technologies were considered. Fig. 1. represents the hybridization scheme. The electricity produced by the solar PV power plant is via DC Voltage. Additional inverters are necessary to convert the DC Voltage to AC Voltage for grid integration through a step-up transformer. However, biomass power generation units directly generate AC voltage and hence no additional inverter is required. The two plants would be integrated to the grid by a common AC bus. The net installed capacity of the system would therefore be the sum of the capacities of the individual components of the hybrid system, namely solar PV and Biomass Gasification.
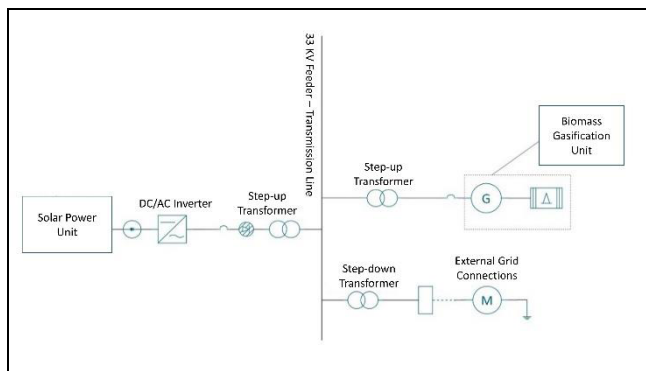

Fig. 1. Layout of the 2MW Hybrid System, 1MW each from Solar PV and Biomass Gasification

3.3 CO₂ Mitigation Potential

Energy generation from onshore wind turbines and solar PV was considered carbon neutral, ignoring lifecycle emissions. Even though biomass to power is considered carbon neutral, net non-negligible emissions result from biomass cultivation, transportation and pre-treatment. Significant emissions with respect to electricity consumption and use of supplementary fossil fuel, occur during construction stage of the project. The net emissions from raw biomass-based power generation unit over a period p (PEp), was calculated based on practical projects [15], according to (1).

$$PE\_p = \{APE\_cul + APE\_pret + APE\_trans\} \times Q\_bio\,,\_p + ECP\_(J,grid,p) \times EFP\_(J,grid) + ECP\_(J,cap,p) \times EFP\_(J,cap) \tag{1}$$

where, APEcul represents the unit CO_2 emissions per tonne of biomass cultivation = 0.0252; APEpret represents the unit project CO_2 emissions from fossil fuel and electricity consumption at the various points of the production chain, including pre-treatment facility = 0.0220; APEtrans represents the project specific CO_2 emissions from biomass feedstock transportation from different locations = 0.0245; Qbio,p represents the quantity of as-procured biomass (in tonnes); ECPJ,grid,p represents the amount of electricity imported from grid for self-consumption over the project in period p [MWh/p], assumed negligible; EFPJ,grid represents the local grid emission factor = 0.7689 kgCO_2/MWh [16]; ECPJ,cap,p represents the amount of off grid electricity consumed by the generator in the project period p [MWh/p], assumed negligible; EFPJ,cap represents the emission factor for captive electricity = 0.8 tonneCO_2/MWh.

Different feedstocks like waste paper or MSW have significantly different CO_2 mitigation potentials, resulting from different system-specific emissions. End of life emissions from waste or read newspapers were calculated based on existing literature [17]. Majority of the emissions results from the release of the energy stored in paper. Hence waste paper to energy was considered as carbon neutral. The net emissions including transport were calculated according to (1) as 0.0245 tonnesCO_2/tonne of feedstock.

4 Comparative Study

A comparative analysis was developed to assess the performances of the stand-alone and hybrid systems based on the both Solar PV and Biomass Gasification stand-alone power plants and the different combinations of hybrid systems combining the two technologies. Based on assumptions and discussions presented above, five alternative system configurations were considered for the comparative analysis as shown in Table 1. The results are analyzed in the following chapter.

Table 1 Systems considered for techno-economic comparative evaluations

Technology	Equivalent System Capacities (MW)	
	Solar PV	**Biomass Gasification**
System A	3	-
System B	-	1
System C	1	1
System D	0.5	1.5
System E	2	0.5

5 Results

Based on the five systems, a comparative analysis was developed towards obtaining the most suitable solution for a small-scale grid-connected renewable power generation system

for production of own green power by SMEs. The results have presented and discussed in the following sections.

5.1 Energy Generation Potential

As can be seen from Fig. 2, the net energy generation of the 3 MW Solar PV power plant is 4.6 GWh, which is less than the annual demand of 5.2 GWh by the printing industry, marked by the blue line. Hence a small scale stand-alone solar PV power plant would be unable to meet the demand by itself in the present case study. However, System B, running entirely on biomass generates 5.256 GWh, slightly higher than the energy demand, due to higher plant capacity factor of 60%.

On the other hand, a hybrid system of Solar PV-Biomass Gasification increases the energy generation considerably. It needs to be mentioned here that due to the complicacy of the biomass supply, as discussed in the previous sections, a lower capacity factor of 50% was assumed for the 1.5 MW system. Conversely, the capacity factor of a 500 KW system was assumed to increase to 70% due to lower needs of the feedstock. Hence, the energy generation potential of Systems D and E were evaluated based on the individual biomass power plant capacity factors.
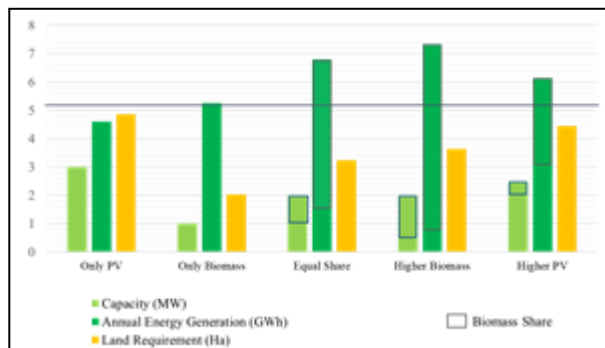

Fig. 2. Comparison between System Capacity Net Energy Produced and share of produced energy from biomass of the alternative systems

The capacity factor of the biomass power plant considerably influences the overall energy generation from a solar PV-Biomass Gasification hybrid system. A higher share of solar capacity within the hybrid system considerably decreases the net energy output, as is evident from System E, even though the capacity factor of the 500 kW Biomass power plant was considered higher at 70%.

5.2 Economic Comparisons

5.2.1 CAPEX and OPEX

Table 2 shows the CAPEX and OPEX of the systems considered. The costs of 1MW solar PV and 1MW Biomass Gasification power plants were determined based on quotes from regional manufacturers and local project details. The capital costs of the equipment and infrastructure for the higher and lower capacity systems were assumed based on the six-tenth rule [34]. Due to a rapid drop in prices of PV panels in recent years, the cost of a 3MW solar PV power plant is comparable to a 1MW Biomass Gasification power plant. Also, the upfront costs of civil and additional infrastructure like storage space, cooling

towers, etc. are either much lower or non-existent for Solar PV systems than the biomass-based power generation unit. Additionally, biomass gasification power plant, comprising gasifiers, cleaning equipment and internal combustion engines are more complex and costly equipment, increasing the overall CAPEX.

Table 2 CAPEX and OPEX of the considered systems

SYSTEM	CAPEX (million $)	OPEX ('000 $/Year)
System A	1.72	56.01
System B	1.78	304.89
System C	2.45	316.343
System D	2.88	460.06
System E	2.39	193.586

Indeed, specific costs of stand-alone systems increase further due to the requirements of dedicated grid connection, electrical systems and administrative infrastructure developments. However, these costs are shared between comprising technologies in a hybrid system, decreasing specific costs of the overall project. The CAPEX of systems D and E hence were determined accordingly.

The system operation costs, including the cost of fuel, is also presented in Table 2. By far, fuel costs increase the overall OPEX of the biomass systems, either stand-alone or hybrid. An increase in capacity of the biomass power plant increases the operating costs of System D. However, the reverse might not always be true. Considering a conservative approach, besides water consumption costs, all other costs were assumed same for a 500KW biomass power unit with regards to that of a 1MW unit.
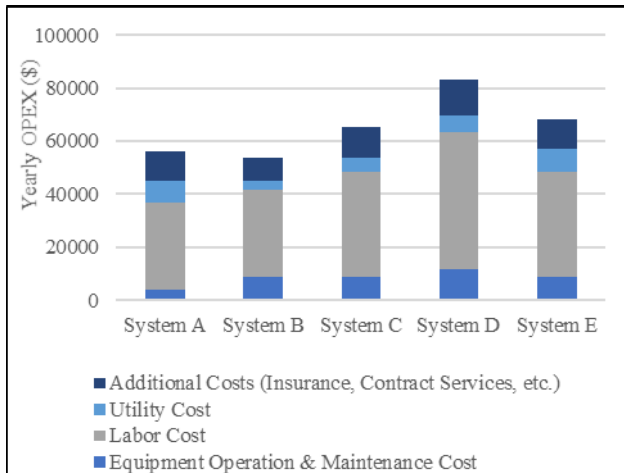

Fig. 3. Components of OPEX of the systems studied

Costs of operation and maintenance, that included annual equipment operation and maintenance cost, labour cost, utility costs primarily in terms of water and electricity, and additional costs including insurance, contract services, etc. The labour wages were divided into wages for the plant manager, maintenance personnel and security personnel, based on local salary levels at 12,000 $, 3,200 $ and 2,000 $ per year respectively. The specific costs of operation for stand-alone systems are higher due to requirements of dedicated personnel, besides, plant managers and security. However, for hybrid systems, even though the requirement of dedicated personnel for each system type may increase, the net specific costs for manpower requirements decrease. A breakdown of the OPEX, without the fuel

cost of the five different systems considered, is shown in Fig. 3, which could potentially be discussed further as to means of decreasing the OPEX for small-scale power generating units.

5.2.2 IRR, NPV, Payback Period and LCOE

The economic performance of the five systems in terms of Internal Rate of Return (IRR), Net Present Value (NPV), Payback Period (PBP) and Levelized Cost of Electricity (LCOE) was evaluated. The feed-in tariff of biomass was 16.67 c$/kWh, as fixed by government incentives. On the other hand, Solar PV tariff is usually tender based and was assumed as 12 c$/kWh. System C, essentially a 2MW hybrid system of 1MW Solar PV and 1MW Biomass Gasification power generation units are presented in Table 3. Besides an attractive IRR and an acceptable LCOE of 10.4 cents $/KWh, a payback period of 4 years makes the system techno-economically quite attractive.

Table 3 Economic performance of System C

Description	Values
IRR (%)	25.4
Net Present Value (million $)	2.38
Payback Period	4
LCOE (c$/KWh)	10.50

A comparison of the economic performance of System C with regards to that of the other systems is presented in Fig. 4. As can be clearly seen, the performance of the System B is the poorest. High capital costs, compared with the considerable cost of fuel results in a stand-alone biomass power plant to be less attractive in comparison to a stand-alone solar PV power system, represented by System A. However, all the hybrid systems have superior performance than the stand-alone systems. Even with varying overall system capacities and relative capacities of the component systems, the overall project cash flow of all the three hybrid systems was obtained comparable.

Additionally, the lower feed-in tariff of the solar PV power plant than that of the biomass system results in the IRR of system A to be lowest. This also results in a project payback of 7 years for the solar PV power plant. in comparison to six years for the stand-alone biomass power plant and four to five years of the hybrid systems. Conclusions regarding the economic performance of the hybrid systems are drawn based on Fig. 4. Clearly, the economic performance of System C is superior to Systems D and E. The higher IRR and NPV results in the payback period to be lowest at 4 years of system C. However, the LCOE of the System E is lower due to the relatively higher capacity of the solar PV within the 2.5 MW system.
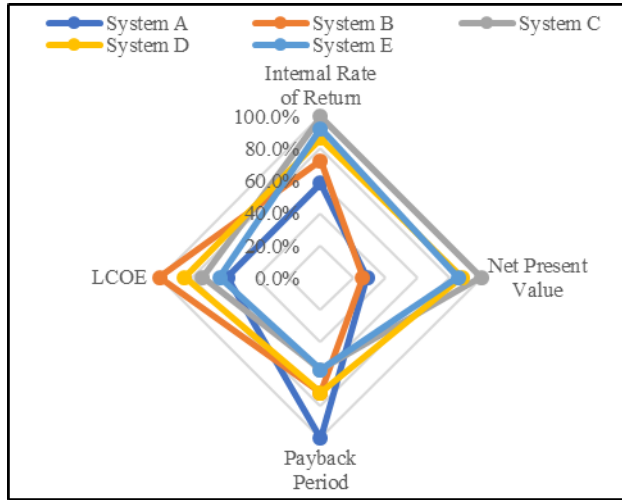
Fig. 4. Economic Comparison of the Defined Systems

The better economic parameters, with the lowest payback period and the highest IRR and NPV makes system C as the most economically attractive among all the hybrid technologies. Incidentally, this system also represents the equal share of capacities of the component technologies of the hybrid system. This additionally helps to balance the techno-economic drawbacks of the individual systems, resulting in higher economic performance.

Table 4 Economic performance of System B and C with a variation of Cost of Biomass Feedstock

Cost of Biomass Feedstock	40 $/tonne		50 $/tonne	
	System B	**System C**	**System B**	**System C**
IRR (%)	18.4	25.4	9.7	22.8
Net Present Value (mn $)	0.62	2.38	-0.056	1.87
Payback Period	5	4	6	5
LCOE (c$/KWh)	14.34	10.50	16.58	17.70

The impact of the variation of the cost of biomass feedstock was studied and the results are shown in Table 4. The impact of the cost of biomass feedstock on a stand-alone biomass power system is much higher than the hybrid system, namely System C increasing the chances of economic failure of a standalone system. The result also shows that the hybrid system is much more resilient to individual system performance variations, as well as against unwanted externalities. Hence, an equal share of capacities in the hybrid system, as seen, would be able to optimize the induvial benefits and drawbacks and present an optimal economic solution for a small-scale grid-connected hybrid power generation unit.

5.3 Operation Strategies

Unlike individual systems, the output from the hybrid system can be effectively controlled to achieve better technical and economic benefits. Between the three hybrid systems studied, the hybrid system with an equal capacity of solar PV and biomass gasification unit has the potential for the highest flexibility of operations. By modulating the biomass power unit, and with complementing capacity factors, the hybrid 2 MW system, with an equal share of capacity between solar PV and biomass gasification, can be set to produce a stable

quantity of electricity, even without storage systems like batteries. Due to the robustness of design of downdraft gasifiers and high part load efficiency of operations of IC Engines, such options are feasible. Hybrid operations of PV during the day and the biomass during the night would, therefore, be an interesting strategy that can allow the integration of such systems to an off-grid electricity network in future.

5.4 Carbon dioxide Mitigation Potential

The potential of decreasing carbon footprints of operations of an SME by renewable energy generation systems was thus analysed. A 3 MW Solar PV power plant is unable to supply the necessary energy demand. Even though the energy generated, amounting to 4.6 GWh is carbon neutral, the remaining energy is consumed at the rate of grid emission factor. Hence the overall system emission saving potential of System A was calculated to be 3536.9 tonnes per year, as shown in Fig. 5, with regards to the specific emissions of the Sri Lankan grid at 768.9 grams per KWh. A net emission reduction of 82% results thus.
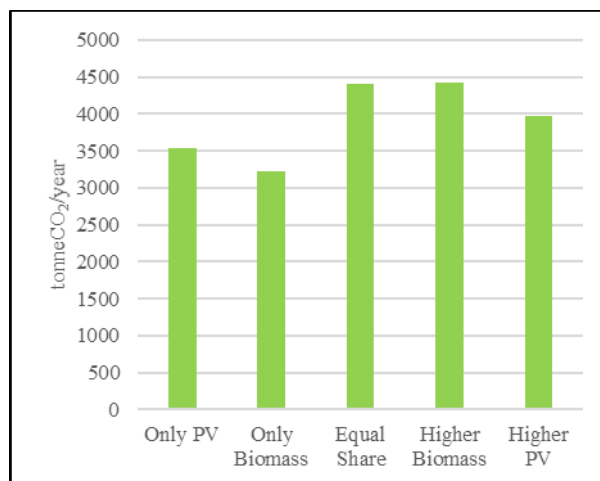

Fig. 5 Emission saving Potentials of the compared systems

Net annual emission of the stand-alone 1 MW biomass gasification power plant fed only with energy crops or agricultural wastes was estimated at 800 tonnes CO2 based on (1). However, the presence of carbon-neutral waste paper, amounting to 20% of energy produced decreases the total emissions further. Therefore, an emission reduction of more than 80% using dedicated energy crops and agricultural wastes, in the form of coconut shells, along with waste paper was calculated to be feasible. Higher energy yields would result in higher absolute emission reduction, as is evident from results between system C and D. However, the increase of biomass power capacity within the hybrid system undermines the increasing energy generation, due to higher specific emissions of the biomass-based system with regards to solar.

5.5 Social and Other Impacts

The land requirement and other social and environmental impacts were assessed in brief. A lower land requirement for biomass power generation, 2 ha/MW would be advantageous against stand-alone solar systems to produce the same energy. However, with a hybrid

system, land requirements for administrative purposes and electric switchgear can be shared among the technologies, decreasing the overall need for land further.

Overall environment impact analyses of the different systems were studied as well. Even though the impact on biotic and abiotic resources was not severe for all the systems, social impact and alteration of the local living patterns might occur. Particularly, inadequate system design of a biomass power system leading to liquid and gaseous effluent emissions might lead to serious social issues, severely affecting the long-term smooth operation of the biomass power, and hence putting the overall project at risk.

6 Conclusions

An analysis of the different small-scale renewable power generation systems was performed specifically to a case study in Sri Lanka. Solar PV and biomass gasification were obtained as the two most suitable technologies for small-scale applications. Grid integration would pose a significant challenge in the future, if not in many situations at present, especially with fluctuating renewables. Among the different hybrid system combinations, a 2 MW hybrid power generation with an equal capacity between solar PV and biomass gasification system resulted in the most suitable option for a small-scale grid-connected hybrid renewable power plant. A superior economic performance, besides robustness of the selected technologies, would further lead to easier installation and operation of such systems by SMEs. A minimum of 80% reduction potential of carbon dioxide emissions for the operations of SMEs was obtained through the hybrid power generation systems. Lower land requirements would be an added advantage towards sustainability of such small-scale power generation units.

Acknowledgements

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