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Life cycle assessment of village electrification based on straight jatropha oil in Chhattisgarh, India

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ABSTRACT

A decentralized power generation plant fuelled by straight jatropha oil was implemented in 2006 in Ranidhera, Chhattisgarh, India. The goal of this study was to assess the environmental sustainability of that electrification project in order to provide a scientific basis for policy decisions on electrifying remote villages.

A full Life Cycle Assessment (LCA) was conducted on jatropha-based rural electrification and then compared with other electrification approaches such as photovoltaic (PV), grid connection and a diesel-fuelled power generator. In summary, the jatropha-based electrification in Ranidhera reduces greenhouse gas emissions over the full life cycle by a factor of 7 compared to a diesel generator or grid connection. The environmental performance is only slightly improved, mainly due to the high air pollution from pre-heating the jatropha seeds. With additional measures oil extraction and overall efficiency could be further improved. However, environmental benefits can only be achieved if jatropha is cultivated on marginal land and land use competition can be excluded. Under these conditions, jatropha-based electricity generation might be a useful alternative to other renewable electrification options, as the technology is very sturdy and can be maintained even in remote and highly under-developed regions.

1. Introduction

Access to electricity is a primary requirement for communication, lighting and small-scale industries, and is a major driver for economic development and social prosperity. Rural electrification thus directly addresses poverty reduction and overall quality of life [1]. Realizing the role that electricity can play in the socio-economic status of the rural population, the Indian Ministry of Power launched the Rajiv Gandhi Village Electrification Programme with a goal of ‘‘power for all by 2012’’. However, there are still thousands of remote villages where extension of the grid is considered as economically unviable and many regions with grid connection are affected by severe and unpredictable shortages of electricity. Consequently, decentralized power generation with renewable energy sources could play a key role in electrifying remote villages, and a number of decentralized electrification projects based on solar, biomass, as well as small-scale wind and

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hydro energy have been established over recent years. However, only few projects attained any degree of self-sufficiency, due to the lack of maintenance facilities or negative environmental and socio-economic impacts [2].

In 2006, Winrock International India (WII) implemented a decentralized power generation plant fuelled by straight vegetable oil (SVO) from *Jatropha curcas L.* [3]. Jatropha is a non-edible and drought-resistant shrub of the family Euphorbiacae, originating in Central America [4]. The seeds of jatropha contain a high-quality oil, which is well suited for energetic use [5]. In contrast to many presently used bioenergy feedstocks, jatropha grows on marginal soils in semi-arid areas. It has even been observed that jatropha can improve the soil structure and protect marginal land against erosion [6] and, therefore, has the ability to reclaim barren land.

However, there exist only a few studies about the environmental impacts of jatropha value chains [7–11]. The current studies focus on jatropha-based transport fuels and show that the renewable energy balance of jatropha biodiesel tends to be superior and the carbon footprint lower, than the fossil reference. However, Reinhardt et al. [9] showed that the environmental benefits due to the reduced release of greenhouse gases (GHG) compared to fossil alternatives might be compensated by environmental disadvantages such as increased acidification and eutrophication.

It can be speculated that electricity production from jatropha is more energy-efficient and less carbon-intensive than producing biofuels. However, reliable information is lacking both on the environmental and the socio-economic impacts of jatropha-based rural electrification.

The goal of this study was to assess the environmental sustainability of the electrification project in order to provide a scientific basis for policy decisions on electrifying remote villages. The study was based on Life Cycle Assessment (LCA) and assessed a pilot power plant in Ranidhera, Chhattisgarh, India. The performance of this jatropha-based rural electrification is compared with other approaches i.e. a central photovoltaic (PV) grid connection and the use of fossil diesel. Key processes with high environmental impacts are identified in order to optimize the current system.

2. Materials and methods

A comparative LCA was conducted according to the ISO 14040 guidelines [12,13]. The inventory data for the different rural electrification scenarios was mainly collected from expert interviews and field observations in Ranidhera, Chhattisgarh. All calculations were done with SimaPro 7.1 software [14].

2.1. *Study site*

The pilot power plant was installed in Ranidhera, a typical Indian village situated in Bodla block of Kabirdham district in Chhattisgarh state (22°02′ N and 81°14′ E). The village is located at the end of a valley surrounded by forested hills. Average annual rainfall is 990 mm and average insolation is 5.5 kWh m^{-2} per day with sunshine on approx. 2200 h per year. Ranidhera counts 118 households (HH) and has a total population of 643.

The village is off grid and the pilot power plant, a diesel genset with 7.35 kW_{mech} and 7.5 kVA run on jatropha oil, is the only power source. The power plant is operated daily for approx. 4 evening hours and is mainly used for lighting and partly for entertainment. Before the power plant was installed, kerosene lamps had been used for lighting.

For the comparison of the four different electrification options, an average village size of 100 households (HH) with a peak load of 1.9 kW (see Table 1) was used. Assuming 5% power loss in the village grid and a demand factor of 100% during the 4 daily operation hours, the peak load at the village bus bar is 2 kW and the energy consumption is 8 kWh per day and 3 MWh per year.

2.2. *Functional unit*

For this study the performance of a jatropha-based energy system is compared to a fossil diesel genset, to a central PV system and to a connection to the grid of Chhattisgarh State (see Fig. 1). The functional unit is defined as 1 kWh electrical energy at the village bus bar. The size and specification of the compared systems meet the defined peak load i.e. 2 kW and 8 kWh electricity supply over 4 h during night. However, operating the currently installed genset (7.5 kVA rated power) on 2 kW load is not efficient. In order to show the optimization potential, a downsized and optimized diesel and jatropha system (see Section 3.1 and 3.2) was added for the comparison.

2.3. *System boundary*

The systems considered consist of all relevant processes necessary for electricity generation, including transport and infrastructure. The local AC distribution and use of electricity are the same for all the technologies compared, and therefore have been neglected. The environmental burden was allocated by economic factors to by-products, such as jatropha press cake. However, the carbon and energy values were allocated according to the stoichiometry and energy content respectively. The disposal of end of life equipment such as engine or expeller was excluded.

2.4. *Inventory building*

Specific data for the cultivation and processing of jatropha was collected from the pilot plant in Ranidhera. The same plant is also able to operate on fossil diesel, and was therefore taken as the basis for the reference system. Specifications and inventory data of the PV system were derived from systems installed

Table 1 – Load distribution assumed for the study.

	Quantity (per Village)	Quantity (per HH)	Power (W)	Total (kW)
Light points	100	1.5	11	1.1
Radios	5	0.05	20	0.1
Streetlights	18	0.18	18	0.32
TVs	2	0.02	40	0.08
Fans	5	0.05	60	0.3
			Total	1.9

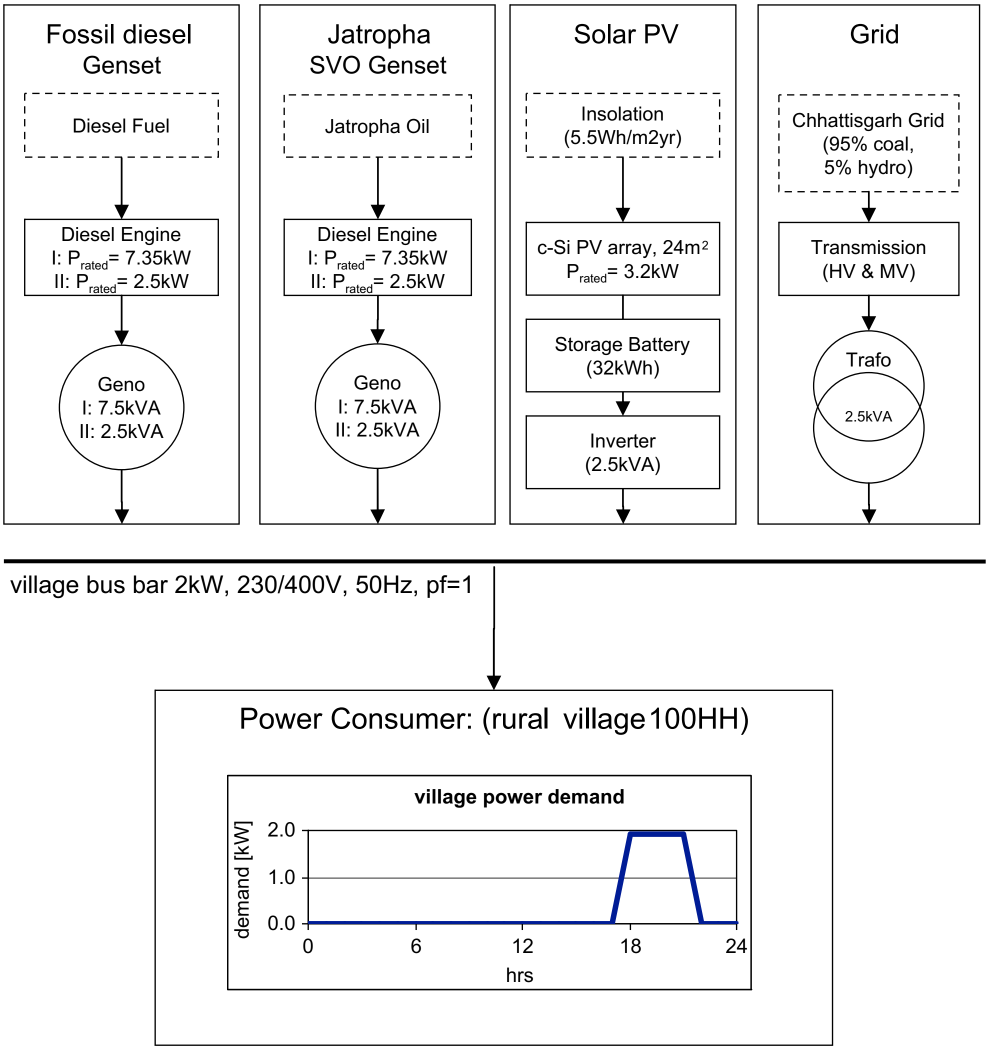

Fig. 1 – Single line diagram for the four electricity supply systems compared. The values of the optimized fossil diesel and Jatropha system are marked with II. The village power demand includes the village grid losses. For specification details see chap 3.

in neighbouring villages. The connection of Ranidhera to the state grid was also modelled for the local set up. Site-specific inventory data was complemented with background data on energy supply, transportation, infrastructure and industrial processes from the ecoinvent database v2.0 [15].

2.5. *Environmental impact assessment*

Presently, no impact assessment method specific to conditions in India exists. Therefore, selected baseline impact categories established by the Centre of Environmental Science of Leiden University (CML) [16] and the eco-indicator 99 [17] were used. Further, the cumulated energy demand (CED) [18] has been measured as MJ input per MJ output. Table 2 provides a list of the used characterization factors.

Various studies show the effect of land transformation on the ecosystem [19,20] and on carbon stock change [10,21]. However, in LCA the environmental impact of land use change is assessed very generically and currently regional and crop specific impacts cannot be assessed adequately. For jatropha it is claimed that planting it has a positive impact on soil fertility, but presently only limited information about the actual impact of occupying marginal land is available [6]. Since in Ranidhera the plants are only planted on marginal soil along the roadsides and in hedges surrounding the agriculture land, the land transformation was assumed to be negligible. As a conservative assumption, the carbon stock linked to land use change was neglected.

3. Compared systems and technologies

3.1. *Reference system: import of fossil fuels*

Approximately 70% of India's crude oil is imported mainly from onshore oil wells from the Middle East and Africa [22]. The main processes linked to the crude oil extraction were taken from Jungbluth et al. [23]. Up-to-date transportation data was used of for hauling the diesel from the refinery at Vizag to Raipur (513 km) by train, from Raipur to Kawardha (136 km) by truck and from Kawardha to Ranidhera (28 km) by tractor.

Table 2 – Characterization factors used in this study.

Impact category	Abbrev.	Unit	Source	Remarks
Cumulated energy demand	CED	MJ input per MJ output	[18]	Split in renewable and non-renewable energy sources (FOSS)
Global warming potential	GWP	kg CO_2 eq.		Factors for GWP 100 years
Respiratory disease caused by Inorganics	RESP	DALY	[17]	(H,A)
Photochemical oxidation	SMOG	kg ethylene eq.	[16]	Factors for high NO_x values
Acidification	ACID	kg SO_2 eq.	[16]	Factors for average Europe
Eutrophication	EUTRO	kg PO_4 eq.	[16]	Generic factors
Ecotoxicity	ETOX	PAF *m^2*yr	[17]	(H,A)
Aggregated impact: Eco-indicator $99_{(h,a)}$	E99	EI'99 points	[17]	(H,A)

The engine and alternator were taken from the jatropha scenario. However, the emission profile and the fuel consumption were adapted for fossil diesel (0.13 kg per MJ E_{mech}). For the "fossil diesel optimized" scenario we assumed 100% load, leading to an increase in the engine efficiency to 35%.

3.2. *Jatropha-based power generation*

Fig. 2 shows the main processes and flows of the jatropha-based pilot plant. The system described reflects the current conditions in Ranidhera, while the number in brackets refers to a technically optimized system.

3.2.1. *Cultivation*

The jatropha saplings were grown in a nursery. When the monsoon started, the three-month-old saplings were transported to the village (100 km) and planted at the edge of fields and roads with a spacing of 2 m × 2 m per plant. In order to enhance the survival rate of the plant, mineral fertilizer (4 g of diammonium phosphate, DAP) and organic fertilizer (3 g solid compost) per plant was applied. The application of fertilizer causes ammonia, N_2O, and NO_x emissions to air, which were calculated according to Jungbluth [24]. For the phosphate and nitrate leaching to water the emission models proposed by Faist were used [25]. Further, we considered the heavy metals contained in the fertilizer as soil inputs. After the critical first year, neither fertilizer nor irrigation was applied. Every five years, 0.04 g per plant of Chloropyrifos 20EC insecticide will be used to protect the shrubs against termites.

During the first two years only a few seeds were produced by the plants. Presently, the plantation is two years old, yielding 0.5 kg per plant and year. Subsequently, a constant yield of 1 kg per tree over the whole lifespan of 50 years is assumed [26]. When the fruits were dry and the hulls started opening, the seeds were collected for oil production, while the husks were left on the field. Cultivation, harvesting and de-hulling were done manually.

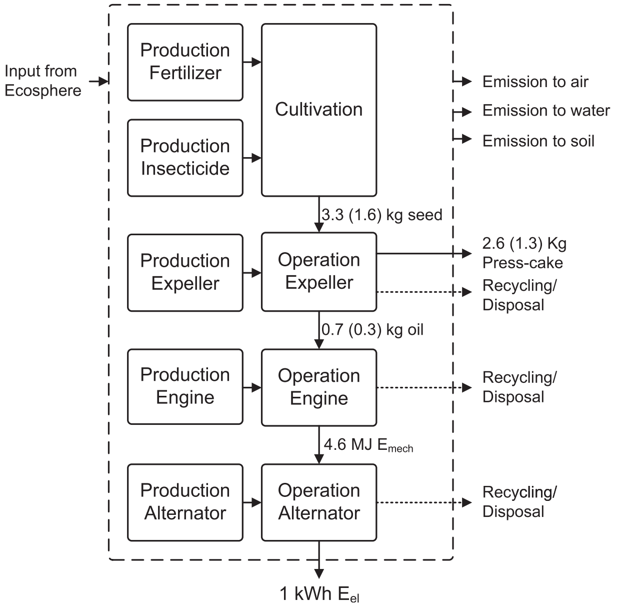

Fig. 2 – Basic process steps of Jatropha-based electricity production. The output values of the main processes are related to the generation of one kWh electricity. The numbers in brackets are related to the optimized systems.

3.2.2. *Oil expeller and filter press*

After drying in the sun, the dry seeds were fed into a screw press to mechanically extract the oil. The expeller had a maximum capacity of 35 kg seeds per hour, and was powered by a 7.35 kW diesel internal combustion engine (ICE) running on jatropha oil. In order to lower the oil point pressure, the seeds were heated before crushing. Therefore, a wood-fired steam kettle was fitted to the expeller. About 2 kg of wood from the forest near-by was used per kg of jatropha crude oil. However, Beerens [27] has showed that the effect of any pre-heating on oil recovery is negligible, and thus such inefficient pre-heating is obsolete. The "jatropha optimized" scenario was therefore modelled without a steam kettle.

After the expelling phase, a reciprocating pump drew the crude oil from the expeller tank and forced it through a series of 12 cloth filters to remove sand and other impurities. Press residues were mixed with seed cake and with fresh seeds for a second round of expelling. 0.21 kg straight vegetable oil (SVO) per kg seed was expelled resulting in an overall oil yield of 21%.

As almost no market for jatropha press cake had ever been established in the area, the cake was sold for only 0.02 €[1] per kg press cake. Nor for the SVO had any market ever been

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[1] Monetary values were calculated from Indian Rupees to Euros at an exchange rate of 0.01513 €/INR, http://www.oanda.com, May 2009.

established in the area, and therefore a value of 0.4 € was calculated, taking into account a seed value of 0.1 €/kg, the price of seed cake and net yield of 21% from the oil expeller.

3.2.3. *Diesel engine run on SVO*

A modified Field Marshall brand diesel engine with 7.35 kW (Model: FMS10) was used. The ICE ran on SVO and operated at a capacity factor of 34%. The fuel consumption was 0.152 kg SVO per MJ E_{mech}, which is equal to an efficiency of 16.4%. Due to the characteristics of the combustion engine, the energy efficiency increases up to 35% whenever the engine is run on 100% load. For the hypothetical scenario ‘‘jatropha optimized’’, a 2.5 kW engine with 35% energy efficiency is considered.

The oil drain interval is 200 h, the sump capacity being 4 L. The crankcase oil used was of a special formulation to counter the higher deposit forming tendency of jatropha oil. The engine has a lifespan of 29,200 working hours. Data for the emission profile of engines run on sunflower oil were used [24] as a proxy for jatropha, since no adequate data had been published.

3.2.4. *Generator*

A 7.5 kVA 3-phase 230 V generator with a max. efficiency of 92% was directly connected to the ICE.

3.3. *Solar photovoltaic (PV)*

The photovoltaic system included photovoltaic modules, a lead acid battery, an inverter and interconnection wiring. The PV system was sized for 100% availability and typical weather conditions, conversion losses and demand fluctuations, which resulted in an installed capacity of 3.2 kWp. The inventory data was mainly taken from Jungbluth et al. [28].

3.3.1. *Photovoltaic modules*

Crystalline silicon photovoltaic modules with 132 Wp/m^2 and a module efficiency of 13.2% were used. Thus, 24 m^2 of total panel area were required for the given load, including a provision for backup. The cells had a lifespan of 30 years. The LCA included the material extraction and the entire production chain of the cells as well as the electrical installation, the mounting on the flat roof top, as well as the disposal of the solar panels.

3.3.2. *Lead acid batteries*

Lead acid batteries are usually used in rural PV projects. The equivalent system requires 22 batteries of 12 V and 150 Ah (ca. 32 kWh), including a 3 day backup capacity. The batteries have an efficiency of 80% and last for eight years. Recycling of the battery was neglected.

3.3.3. *Inverter*

A standard inverter with an average conversion efficiency of 93.5% was used.

3.4. *Connection to the national power grid*

This scenario includes the extension of the regional power grid of Chhattisgarh to Ranidhera. The electricity mix is 95% coal and 5% hydropower [29]. Imports and exports from neighbouring states are negligible (1%).

3.4.1. *Power generation*

As a proxy the performance of a typical Chinese hard coal power plant was used for the model [30]. The capacity of the plant considered was 300 MW and the system operated at an efficiency of 34.8%. The performance of hydro-based power generation was assessed using data from Swiss hydropower plants for dam-mixes in non-Alpine countries [31]. The average net efficiency, including penstock losses, is 78%.

3.4.2. *Transmission and distribution*

Once generated, power is fed into the transmission and distribution network to supply the consumers. As part of the study, high, medium and low voltage grids were modelled. Total transmission and transformation losses were assumed to be 8%, which is a Chinese proxy [32].

4. Results

4.1. *Energy balance*

Fig. 3 shows the cumulated energy demand (CED) for various electrification options. While the overall energy demand for the Jatropha- and PV-options is higher than for the fossil reference, the non-renewable energy demand is by factors better for the Jatropha- and PV-options as compared with the reference cases.

4.2. *Environmental performance of jatropha-based electricity*

Table 3 summarizes the contribution of life cycle stages to the global warming potential, as measured in kg CO_2 eq., as well as to the overall environmental impact, as measured in eco-points. In total, the generation of one kWh electricity is linked to the emission of 0.27 kg CO_2 eq. and has an environmental burden of 0.088 Eco-Indicator 99 points.

Regarding GHG emissions, the main impact is linked to the process chain of jatropha seeds (79.3%), while the cultivation of jatropha seeds itself causes 20.7% of the total emissions. The combustion process of the engine and the construction of the power plant building released 0.11 kg CO_2 eq. (31%) and 0.09 kg CO_2 eq. (26%) respectively.

The environmental impact is caused mainly by processing the jatropha seeds and oil (75.2%). The main factor of 52.7% is attributable to the inefficient combustion of the wood logs in the steam kettle that released particulate matter affecting human health.

4.3. *Overall environmental impact of compared systems*

In Fig. 4 the aggregated environmental impact and the GWP of the jatropha-based system is compared to alternative systems. While environmental impacts of the jatropha scenario are on the same range as that for fossil diesel or a grid connection, GWP is 6 times lower than for diesel or grid. In absolute terms, more than 1.5 kg of CO_2 equivalent can be saved per kWh electricity generated using the jatropha system. The PV system outperforms in both parameters all other compared systems.

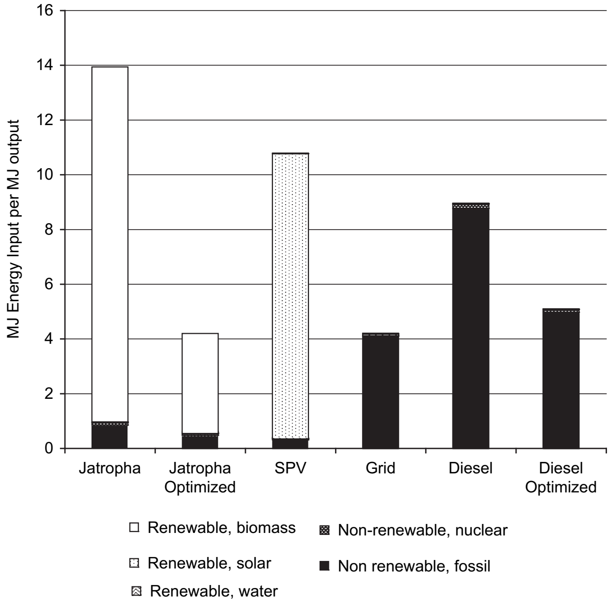

Fig. 3 – Cumulated Energy Demand measured as total energy input over electrical Energy output in MJ. The values are classified according to their energy source.

However, waiving the boiler process and optimizing engine load (scenario "jatropha optimized") would bring the jatropha scenario close to the solar PV scenario.

Fig. 5 shows the detailed characteristics of the environmental impacts of each electrification system. However, since the impact categories are not normalized and weighted against each other, no conclusion about the relevance of each impact category can be drawn.

4.3.1. *Non-renewable resource depletion (FOSS)*

The impact due to fossil resource depletion is obviously quite low for renewable systems. The main impact for fossil diesel system comes from the depletion of crude oil (634 gkW h^{-1}). For grid based electricity, the high impact is linked to the depletion of coal reserves (612 gkW h^{-1}).

4.3.2. *Respiratoric inorganic (PM)*

The jatropha system releases large amounts of respiratoric inorganics due to the combustion of firewood in the steam kettle. In the case of grid electricity, the extraction and especially the combustion of coal also results in relatively high emissions of particulate matter.

4.3.3. *Photochemic oxidants (summer SMOG)*

The jatropha system shows the highest impact on summer smog due to the relatively high release of carbon monoxide. 86% of the carbon monoxide is released during the combustion of firewood used in the steam kettle. Regarding the grid system, the main contributor to summer smog is the extraction of coal (17%) and the coal based power plant (71%). The large contribution is caused by the release of sulfur dioxide (88%) and methane (10%). The PV and fossil diesel systems showed relatively low impacts.

4.3.4. *Acidification (ACID)*

Acidification is mainly caused by conventional electricity systems. The relatively high impact of fossil diesel is caused by the release of nitrogen and sulfur oxide during refining and the combustion process in the engine. The operation of the coal based power plant causes 82% of the acidification effect of the grid electricity, mainly due to the released nitrogen oxides (15%) and sulfur dioxides (84%).

4.3.5. *Eutrophication (EUTRO)*

The jatropha system showed a relatively large eutrophication effect. The emissions are mainly caused by the phospate (51.5%), phosphorus (34.5%) and nitrate (11.4%) leaching to surface and groundwater.

4.3.6. *Ecotoxicity (ETOX)*

The ecotoxic effect of the compared systems was relatively balanced. However, the jatropha and fossil diesel systems showed a slightly larger impact. The main contribution of the fossil diesel system originated in the combustion of diesel (77%) and the refining process (20%). Both processes release great amounts of NO_x. For the jatropha system, the combustion of firewood (55%) and the construction of the power plant (27%) contributed most to the ecotoxic effect. The engine itself did not contribute significantly, since the emissions of NO_x were much lower than the diesel system's.

5. Discussion

In summary, the jatropha-based electrification in Ranidhera reduced greenhouse gas emissions over the whole life cycle by a factor of 7 compared to a diesel generator or to a grid connection. Nevertheless, environmental performance was improved only slightly, a fact due mainly the severe air pollution caused by pre-heating the jatropha seeds. Overall, the environmental performance of the PV system was superior in all aspects considered.

Even though renewable energy systems show generally low environmental impacts and global warming potential, the impacts in certain categories are typically higher than the fossil reference. The jatropha system showed, for instance, a relatively large eutrophication effect, although only small amounts of fertilizer were applied. Furthermore, the release of photo-oxidants and particulates caused a relatively high impact on human health.

5.1. *Improvement potential*

The environmental performance of the jatropha system could be improved substantially, as shown in Figs. 4 and 5. An expelling process without using a steam kettle reduces the release of particulates and, thus, reduces the overall environmental impact by more than 50%. Expelling devices that do not require a steam kettle do exist, and some even attain higher oil extraction efficiencies. Furthermore, engine efficiency could almost be doubled by running the engine at its point of optimal efficiency, i.e. at full capacity, by decreasing the engine size or increasing the load. Adding consumers, paddy de-husking machines or electric tools e.g., would not

Table 3 – Absolute and relative global warming potential (GWP) and overall environmental impact of the modelled life cycle stages. The values refer to the generation of one kWh electricity and are measured in g CO_2 eq. and Ecopoints 99 respectively. The sequestration of biogenic CO_2 during Jatropha cultivation and consequently also the biogenic CO_2 emissions in the combustion process are not accounted for in the table.

	GWP				Eco-Indicator 99			
	Jatropha		Jatropha Opt.		Jatropha		Jatropha Opt.	
	g CO_2 eq	%	g CO_2 eq	%	mPt	%	mPt	%
Total Jatropha	268.47	100.0	133.13	100.0	88.06	100.0	24.12	100.0
Cultivation	55.49	20.7	25.40	19.1	21.82	24.8	10.12	42.0
Production of diammonium phosphate	40.55	15.1	18.55	13.9	7.05	8.0	3.22	13.4
Production of compost	1.81	0.7	0.83	0.6	0.02	0.0	0.01	0.0
Production of insecticide	9.54	3.6	4.36	3.3	0.94	1.1	0.43	1.8
Transport, lorry 7.5–16t, EURO3	1.32	0.5	0.60	0.5	0.11	0.1	0.05	0.2
Transport, tractor	1.06	0.4	0.49	0.4	0.10	0.1	0.05	0.2
Field emission	1.21	0.5	0.57	0.4	13.60	15.4	6.36	26.4
Operation of expeller	128.22	47.8	48.73	36.6	54.06	61.4	4.36	18.1
Construction of building	62.60	23.3	36.62	27.5	5.25	6.0	3.07	12.7
Production of expeller	10.04	3.7	5.95	4.5	1.09	1.2	0.65	2.7
Transport, lorry 16–32t, EURO3	11.56	4.3	5.29	4.0	0.97	1.1	0.45	1.8
Wood logs, burned in open fire	43.12	16.1	0.00	0.0	46.45	52.7	0.00	0.0
Energy, 10HP engine, Jatropha oil	0.91	0.3	0.88	0.7	0.30	0.3	0.20	0.8
Operation Engine	62.87	23.4	44.52	33.4	9.37	10.6	7.15	29.6
Construction of building	13.41	5.0	7.85	5.9	1.13	1.3	0.66	2.7
Production of engine	3.20	1.2	1.93	1.4	0.35	0.4	0.21	0.9
Production of lubricating oil	9.52	3.5	6.21	4.7	2.50	2.8	1.63	6.8
Transport, lorry 16–32t, EURO3	3.94	1.5	1.80	1.4	0.33	0.4	0.15	0.6
Combustion emission, engine 10HP	26.45	9.9	20.53	15.4	5.01	5.7	4.45	18.4
Disposal of used mineral oil	6.34	2.4	6.20	4.7	0.05	0.1	0.05	0.2
Operation Alternator	21.88	8.1	14.47	10.9	2.80	3.2	2.49	10.3
Construction of building	13.41	5.0	7.85	5.9	1.49	1.7	1.02	4.2
Production of alternator	5.06	1.9	5.06	3.8	1.18	1.3	1.18	4.9
Transport, lorry 16–32t, EURO3	3.40	1.3	1.56	1.2	0.13	0.1	0.29	1.2

only improve environmental performance but also contribute to the socio-economic development of the village.

The environmental performance of the press cake was modelled based on a very low value, as the cake is presently not used. However, the press cake has a number of possible uses, e.g. as (a) fertilizer, (b) feedstock for producing biogas used for cooking/lighting and the slurry as fertilizer and (c) fuel briquettes used in households or small-scale industries [33]. As 4 kg press cake is produced per kg oil, the optimal application of the cake should be carefully evaluated. Besides the environmental relevance of an appropriate use of the press cake, the added value will be crucial for the electrification project's overall economic performance and therefore for its long-term success.

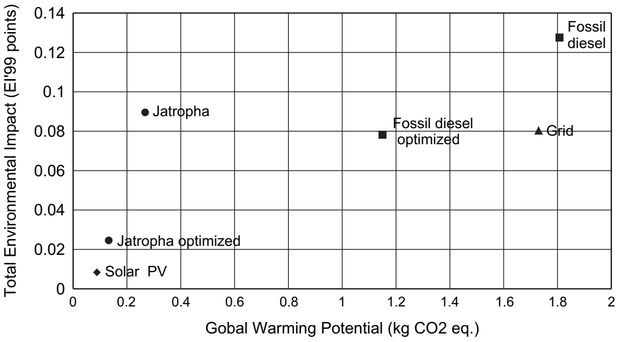

Fig. 4 – Aggregated environmental impact (EI'99) and GWP 100a (kg CO_2 eq.) of electrification systems compared.

Finally, the cultivation of jatropha could be optimized as knowledge on best cultivation practice and seed material is currently improving. Therefore, replicates of the pilot plant, seed material, pruning, application of fertilizer, irrigation, and pest control management could be further optimized to maximize yield while minimizing environmental impacts.

5.2. *Limitations of the study*

Life cycle assessment typically requires a huge set of data and model assumptions. Some aspects, especially concerning data quality and model accuracy, need to be further elaborated.

Presently, the plants in Ranidhera are not yet mature and thus the yield figures need to be observed closely and adapted accordingly. Furthermore, the long-term impacts of cultivating jatropha are presently unknown, as studies on the impacts on biodiversity and soil quality are lacking. Another issue is the toxicity of jatropha- of special interest are phorbol esters and their impact on ecosystems and on humans, which is presently not fully understood [33]. Due to the lack of data, the specific impacts of toxic substances were not covered in this study and need to be updated when more information becomes available.

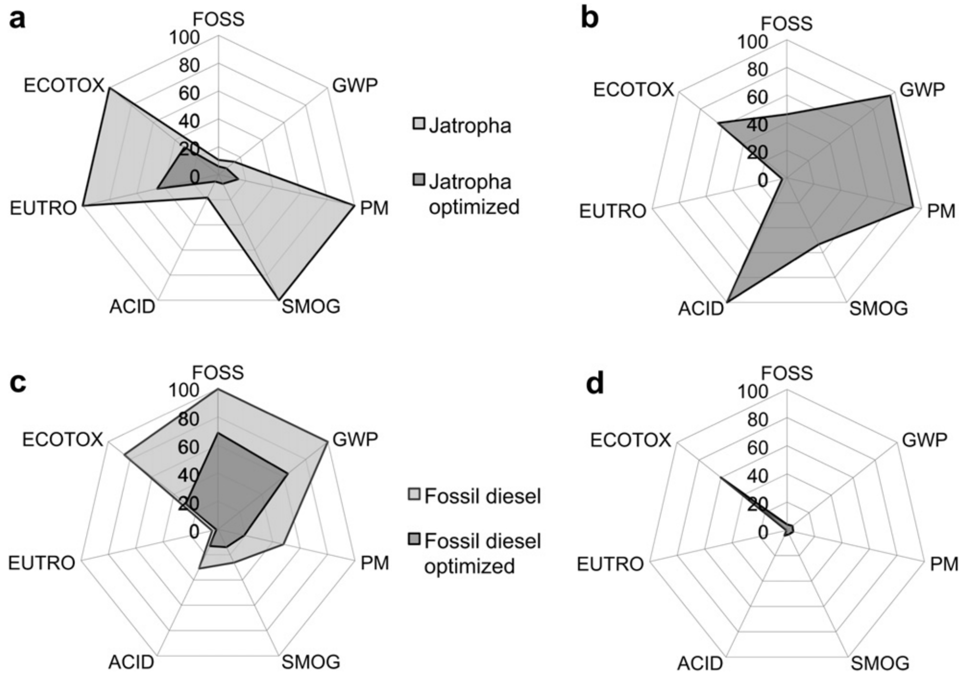

Fig. 5 – Mid-point indicators for the generation of 1 kWh electricity from a) Jatropha, b) grid connection, c) fossil diesel and d) PV system. 100% indicates the highest impact of all systems for each indicator: non-renewable resource depletion (FOSS), respiratory inorganic (PM), photochemical oxidants (summer SMOG), acidification (ACID), eutrophication (EUTRO), ecotoxicity (ETOX).

Furthermore, the disposal of the solar battery was neglected in the present study, since the respective impact factors were missing in the environmental impact assessment models. Nevertheless, it is possible that the batteries are not properly recycled, and that lead or sulphuric acid leaches into the soil or water.

Also the methodological approach used in the present study exhibits certain limitations. LCA is used to estimate the environmental impacts over the entire life cycle. However, presently there are no environmental impact models available for India and therefore standard European indicators were used in their place. In order to gain a full view of the sustainability of jatropha-based rural electrification, LCA needs to be further adopted to the environmental conditions prevailing in India, and then complemented with socio-economic impact assessment.

6. Conclusion

This study has shown that rural electrification based on extensive jatropha cultivation is environmentally friendly compared to the usage of fossil diesel or to connection to the local grid. The optimization of the expelling process and the operation of the engine under full load might further improve environmental performance. However, significant environmental benefits can only be achieved if jatropha is cultivated on marginal land. Therefore, land suitability has to be assessed carefully before implementing jatropha-based electricity systems. Under these conditions, jatropha-based electricity generation may be a useful alternative to other renewable electrification options, as the technology is very sturdy and can be maintained even in remote and highly under-developed regions.

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