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"Tropicalisation" of Feed-in Tariffs: A custom-made support scheme for hybrid PV/diesel systems in isolated regions

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ABSTRACT

The interest and actions towards introducing renewables for off-grid regions has increased due to their ostensible cost-effectiveness, eco-friendliness and quality services provided. Nevertheless, in many isolated areas diesel generators appear as a common option, confirming that there is a need for financial support mechanisms that aid the introduction of renewables due to their higher initial investment costs.

This paper proposes a so-called 'tropicalisation' of the Feed-in Tariff scheme to promote the introduction of hybrid systems in isolated communities based on the idea of awarding for each kWh produced by renewable energies a premium value during a guaranteed period of time. The proposed Renewable Energy Premium Tariff (RPT) scheme is an alternative mechanism to the usual initial investment donation for off-grid energy development projects by recognising the production of renewable electricity and opting for a long-term sustainability of the projects. Ecuador presents ideal conditions to study the introduction of such a 'tropicalised' scheme since a Feed-in Law including off-grid projects was established in 2002 and since there are governmental and local efforts for the introduction of renewable hybrids in isolated regions.

Modelling of the introduction of photovoltaics (PVs) into diesel systems for several mini-grids located in isolated regions of Ecuador has been performed, and included a detailed financial analysis for optimisation of RPT values and a comparison with existing stand-alone diesel systems. The results show the cost-effectiveness of PV/diesel hybrids over diesel gensets, taking into account present and future diesel prices. To obtain long-term sustainability of the project, the RPT values are set at 0.70–1.20$ kWh covering the operability of the whole system for 20 years, where the renewable fraction should have the largest share in the hybrid system. The proposed mechanism is expected to aid the introduction of renewable technologies to bring solutions and sustainable energy options to final users of off-grid isolated regions.

Contents

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1. Introduction

Currently, there are more than 1.6 billion people in the world without access to electricity according to the World Energy Assessment Report [1]. Most of these people are in the remote rural areas of developing countries, which are isolated from the electricity grid due to the geographic location and limited commercial value.

Some governments around the world have tried to bring electricity to remote communities where grid-extensions are not a feasible option through the introduction of diesel generators because they represent an initial low-cost investment [2]. In the long-term these solutions have proved, on their own, to be inefficient due to high operating costs and to the damage they cause to the environment. In addition, diesel-stand-alone systems provide a limited, inefficient and low quality service with constant blackouts. Although they continue to be a less expensive option in the very short-term this is mostly due to direct and indirect subsidies given to fossil fuel based systems [3].

The present activities towards electrification of isolated regions has basically been approached with stand-alone systems (SASs), and mini-grid systems (MGSs), (which can be based on diesel, mini-hydro, biomass, wind, solar power or a hybrid combination), or patience (waiting for the grid to arrive). Renewable MGSs combine the use of renewable technologies depending on the available resources in the region, with conventional decentralised energy technologies and storage systems. They represent one of the best-existing options to bring electricity to isolated and rural areas. Their flexibility allows them to be easily introduced technically and adapted to the most remote areas. Under appropriate conditions, decentralised hybrid systems are already economically competitive and can lead to the improvement of social welfare and living conditions [4]. However, there is still limited experience and research on the implementation of renewable MGSs. Mini-hydro projects presently installed are in the order of ten thousand systems, mainly in Asia, while in the case of PV and wind hybrid MGSs only around one thousand projects have been completed so far in developing countries, mostly in China and India [5,6]. Recently, it has been shown that renewable hybrid options (not only mini-hydro, but also solar and wind) are becoming more attractive and cost-effective solutions [7], emphasising that there is a need to improve support schemes that can stimulate the introduction of renewable MGSs.

A policy support mechanism that has achieved 'unimaginable' results in deployment of renewable energies is the Feed-in Tariff (FiT) Law. In developed countries, FiTs have proven a success, mostly in Germany, Spain and Denmark, where the renewables market has seen an enormous growth in the last few years [8–11]. A FiT offers a long-term contribution to investors on a basis of the electricity generated with renewables and fed into the grid. Among the main benefits identified for a guaranteed tariff are that it is effective, flexible, fast and easy to install and has low administration costs [11]. Currently, in the introduction of renewable energy for rural electrification, subsidies, donations, fee-for-service, and credits are among other financial supports commonly used [12]. The Working Group 4 (WG4) of the European Union Photovoltaics Platform (EU PV Platform) has presented a new concept adapting the FiT mechanism into a "Renewable Energy Premium Tariff" specifically designed for mini-grids employing renewable energy technologies [13,14]. Under the idea of financing 'renewable energy produced' rather than financing 'renewable energy projects', seeking to secure their long-term operability. It appears to be an alternative scheme that can attract further investment in renewables in off-grid areas of developing countries.

The new concept for the variation of the FiT could bolster rural electrification, but demonstration projects are required to fully prove its effectiveness. This paper seeks to take a step further in an attempt to 'tropicalise[1]' the FiT scheme. Preliminary studies of the applicability in different MGSs will determine whether such a mechanism can be effective to further promote electrification of rural and isolated regions in developing countries.

2. Electricity sector and Feed-in Tariffs in Ecuador

The FiT scheme was introduced in Ecuador already in 2002. By 2006 a special and new approach was given to the regulation, where off-grid systems were included in the coverage of the regulation (with the idea of benefiting the Galapagos Islands, but also to provide further impulse to rural and isolated electrification). Regulation 09/06 of Ecuador recognises the production of renewable electricity for both grid-connected and off-grid renewable systems assigning the following values presented in Table 1.

The tariff has been set for 12 years and a limit has been placed for a maximum of 2% of the total installed capacity (i.e. 67 MW in 2007). Unfortunately the policy has not been very effective as it is only a regulation and does not have the power of a law. In addition, it was drafted by *Consejo Nacional de Electricidad* (National Council for Electricity, CONELEC) with little support from the government and currently there is a limited amount of projects benefiting from it [16]. The payment of the FiT is still a complicated and bureaucratic process that has de-stimulated many organisations. Nevertheless, CONELEC is interested in the positive effects this regulation can have and is seeking for further support from the government. CONELEC wants to make it an instrument that can aid them in diversifying their energy matrix and take advantage of the vast natural resources available in the country.

3. PV/diesel hybrid mini-grid systems

An extended number of studies confirm that there is a vast potential for the introduction of PV/diesel hybrid systems in

[1] The term 'tropicalisation' is commonly used when a product, service or practice needs to be adapted to the idiosyncrasy of the place where it will be introduced.

Table 1
Prices recognised by Ecuador's FiT (Regulation 09/06, CONELEC, 2008).

Technology	Price (cUSD/kWh) Mainland	Price (cUSD/kWh) Galápagos Islands
Wind	9.39	12.21
Photovoltaic	52.04	57.24
Biomass and biogas	9.67	10.64
Geothermal	9.28	10.21
Small-hydro up to 5 MW	5.80	6.38
Small-hydro 5–10 MW	5.00	5.50

off-grid areas in Ecuador [17], in the Brazilian Amazons [18], in Latin America [19]; Saudi Arabia [20,21], India [22]; Cameroon [23]; Australia [24]; Peru [25]; and in the Maldives [26]. Not only their cost-effectiveness is already an advantage, but also there are inherent social and environmental benefits to renewables. From 1990 to 2005 a total estimated capacity of 300 MW of off-grid PV has been installed worldwide at an average annual growth rate of 17% [27]. An estimated 10,000 MW of diesel generators are installed in off-grid regions that represent the possibility to introduce renewable hybrid systems. Hence an effective mechanism that aids the introduction of PV into off-grid areas is of great value.

3.1. Hybrid systems in Ecuador

In Ecuador a first step was taken towards introducing hybrid systems to off-grid areas in the Galapagos Islands to replace diesel gensets [28], due to the strong support from the international community. One PV/diesel MGS (22.5 kWp of PV) has been installed in Floreana Island and a large Wind/diesel grid system (2 MW of wind power) in San Cristobal Island, which was inaugurated in 2008. Other hybrid projects are in the pipeline for Isabela Island, 700 kWp of PV to be installed and in Santa Cruz Island 3.5 MW of wind power and 120 kWp of PV. Outside the Galapagos, a PV-alone MGS was installed in 2005 in the community of Y del 5to Piso (Esmeraldas Province) serving 20 families with 3 kWp installed [29].

The government has seen the positive results obtained in the islands, and seeks to continue their efforts and solutions to be replicated in other areas of the country that could benefit from such systems. The *Ministerio de Electricidad y Energias Renovable* (Ministry of Electricity and Renewable Energies, MEER) and CONELEC have approved this year the funds to introduce a PV/diesel MGS in Puná Island based on the feasibility study by Galarza [30] and a PV/hydro/diesel hybrid system in San Miguel Community is also in the pipeline [31].

In addition, Energy Service Companies (ESCOs) have shown an interest to introduce renewables into their MGSs currently running on diesel, due to the high costs and complexity of operating such systems, i.e. Nuevo Rocafuerte (170 kW), Tiputini (400 kW), Bellavista Island (45 kW), Costa Rica Island (55 kW), Palma Real (100 kW), Puerto El Carmen (500 kW), Palma Roja (80 kW), among others. Other regions have been identified by the MEER [32] where possibly renewable MGSs can be installed and could be potential candidates and where currently the ESCO is not providing any kind of service (Telembí, Cerrito los Morrenos, Isla Santay, among others). As well, there are several communities being served by diesel generators donated and maintained by the municipalities or oil companies. Although some of the communities are quite disperse, there is usually a concentrated part, where a few houses are located along with a communal centre, school, health facility, public lighting and other facilities, e.g., in the Aguarico Canton, the Municipality has installed more than 20 small (2.5–5 kW) diesel generators for communal centres to give a few hours of electricity [33]. These communities could benefit from a MGS. Houses that belong to the community and are more disperse can be served with stand-alone systems or by grouping of a few houses with smaller grids, in case they are close to each other.

Although the amount of agglomerated isolated communities without access to electricity appears not to be significant (being mostly disperse communities), this number has not been yet determined. In the reports from CONELEC they specify only the communities served by diesel generators from the ESCOs, where 12% of the electricity generated in Ecuador is not connected to the *Sistema Nacional de Interconexion* (National Interconnection System, SNI), of which 95% comes from internal combustion engines [34]. Data from the Instituto Nacional de Estadisticas y Censos de Ecuador (National Institute of Statistics and Census of Ecuador, INEC) surveys, households served by diesel generators are accounted as electrified (even if only for a few hours). Hence, there is a gap of information that needs to be filled (to know the amount of agglomerated communities with or without access to electricity that can be served by MGSs). Typically, in Latin America there are cooperatives or government units and some private entrepreneurs managing such systems. It is common that they operate in an 'informal' way, hence rarely appear in government statistics [35].

There are also several communities in the Amazons that have diesel mini-grids installed by oil companies. CONELEC recognises the need to properly evaluate decentralised solutions versus grid-extension and independent diesel-based generation. In addition, the needs to identify, quantify, and localise the rural unattended demand. There is a lack of information from fieldwork that can properly reflect the reality in these regions [36]. Hence, it would be important to identify and differentiate the communities without access to electricity and the ones with a limited access (diesel-based). CONELEC already launched a national initiative for all mini-grid systems ($<$1 MW installed powered) to be properly registered [15].

4. Case study: introducing a PV/diesel hybrid in Costa Rica Island

Costa Rica Island is a small town in the Jambelí Archipelago with 250 inhabitants. Electricity is provided to 70 households with a 55 kW diesel generator (see Fig. 1 and Table 2 for characteristics), since 1975 by the local energy service company, *Empresa Eléctrica El Oro* (Electricity Company of El Oro, EMELORO). The service is limited and intermittent (see primary load profiles in Fig. 2) due to the fact that in Jambelí Archipelago it is difficult to acquire diesel and it requires a vast amount of bureaucracy to avoid oil smuggling to the close border of Peru [37].

This section presents a technical analysis for modelling the introduction of PV into the existing stand-alone diesel system with the aid of the Optimisation Model for Distributed Power, HOMER. The HOMER software simplifies the task of evaluating designs for off-grid power systems taking into account different design configurations and allows making sensitivity analyses to determine the optimal set-up of a system according to its life-cycle costs [38].

The technical specifications of the generator such as size (kW), capital costs ($/kW), replacement costs ($/kW),[2] operation and maintenance costs ($/h) and lifetime[3] of the diesel generator were gathered from the information provided by the local electricity companies, the technicians in charge of the generator and manufacturers. Prices given (for diesel generators and likewise for the PV technology) were converted to 2007$ using the

[2] Diesel generators are a mature technology, therefore major costs reductions are not expected to decrease in the medium or long term.

[3] Generator lifetime (h): in the sites visited, generators would last from 1 to 5 years, with most of them ranging in the lower lifetime line. The lifetime varies according to the handling of the generator, i.e. its proper maintenance and adequate operation.

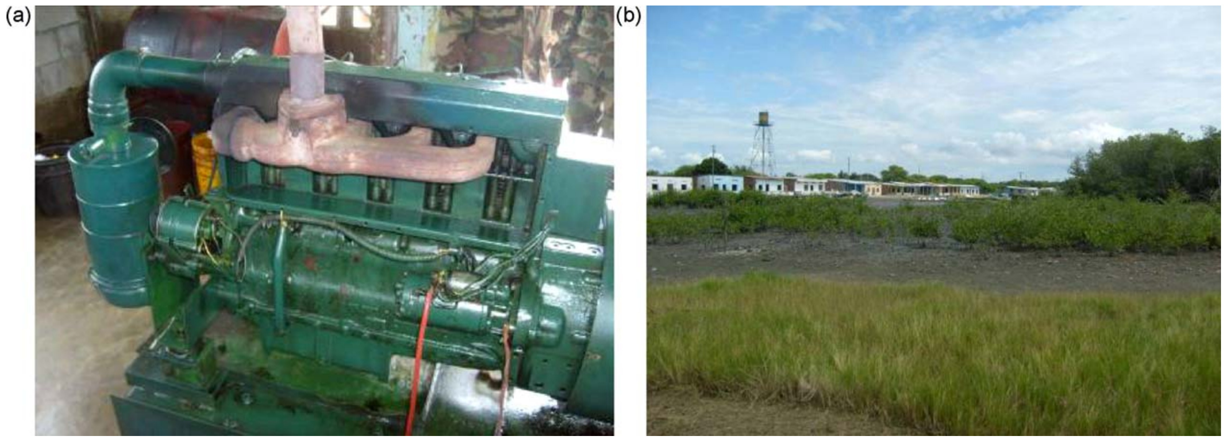

Fig. 1. (a) Deutz Generator operating in Costa Rica Island and (b) Costa Rica Island community.

Table 2
Costa Rica Island Diesel Generator characteristics in low, average and high values to consider uncertainty from different sources.

	Details		
Generator size and model	55 kW (Deutz Engine Model: F5L912 with a Petbow Generator Type: 44ZA7V)		
Daily schedule	06:00–08:00, 12:00–14:00 and 18:00–22:00 (weekdays) 12:00–14:00 and 18:00–23:00 (weekends)		
Diesel price + transportation ($/l)	~0.31[a]		
Operator's salary ($/year)	7000		
	Low	Average	High
Capital cost ($/kW)	300	400	500
Capital recovery cost ($/kW)	300	400	500
O&M costs ($/h)	0.94	1.32	1.7
Lifetime (h)	10,000	15,000	20,000
Fuel consumption slope (l/h/kW output)	0.235	0.294	0.353

[a] Diesel prices in Ecuador are highly subsidised by the government. This value includes the transportation costs by land and river to Costa Rica Island.

consumer's price index from the *Banco Central del Ecuador* (Ecuador's Central Bank, BCE) [39].

Fuel efficiency values (l/kWh) can be obtained from the manufacturers, but more accurate values are obtained calculating efficiency by the annual kWh generated versus the amount of fuel consumed during the year. It is clear that at lower operating powers the generator is less efficient, i.e. consumes more litres per hour to generate a lower amount of kWh. Reason enough for properly dimensioning the size of the generator to be used.

Capital costs of diesel generators vary significantly in literature and between manufacturers, ranging from 200 to 1000$/kW. The most common values retrieved were taken to determine the capital costs, lifetime, and fuel consumption. As well, higher and lower limits were taken to consider uncertainty in the values collected from different sources (see Table 2 for values of the diesel generator operating in Costa Rica Island).

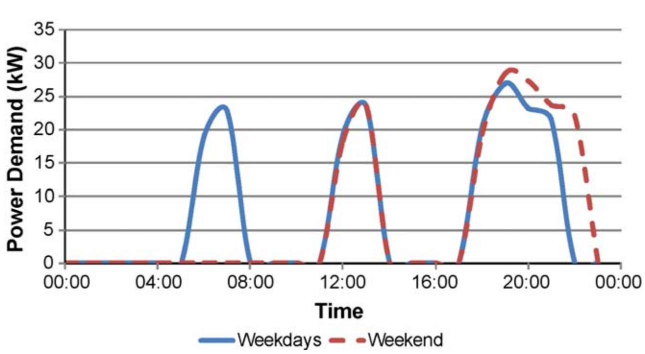

Fig. 2. Current daily demand curve in Costa Rica Island.

4.1. Primary load

To construct the demand curve the primary load was determined by the hourly electric demand throughout the day. The hourly amperage data were collected from the technician's manual record in each phase of the generator, while the voltage is specified in the generator's characteristics.

The following equation [40] was used to determine the output power of the three-phase generator every hour:

$$P = \sqrt{3} \times V \times I \times \cos\varphi$$

P is the output power (W); V is the phase voltage (V); I is the phase current (A); and $\cos\varphi$ is the power factor.

The power factor, $\cos\varphi$, can be regarded as a measure of the efficiency with which the current in a circuit is used [41].

The primary load was calculated by:

$$PL = P - AX - L$$

PL is the primary load; P is the output power; AX is the auxiliary consumption (~5% of output power); L is the losses (case dependent).

Primary load values for weekdays and weekends (see Fig. 2) were calculated independently, taking their average values throughout the year. Also assuming that seasonal variations are not expected, since consumption is rather stable along the whole year.

4.2. Determining the current levelised cost of electricity

To determine the average cost per kWh of useful electrical energy produced by the diesel mini-grid in Costa Rica Island the current values gathered from the ESCO reports were used. Table 3 presents the electricity generation values obtained from the HOMER model, assuming the generator is operated all the time it has been scheduled.[4]

The levelised cost of electricity, LCOE, is defined by:

$$LCOE = \frac{C_{ann,tot}}{E_{prim,AC} + E_{def}}$$

[4] Currently the diesel generator is operated only 87% of the time it has been scheduled, consuming approximately 19,000 l of diesel and producing 53 MWh according to EMELORO generation reports.

Table 3
Values of current electricity generation in Costa Rica Island.

	Values
Electricity produced (kWh/year)	62,770
Electricity introduced in the grid[a] (kWh/year)	61,685
Electricity excess (kWh/year)[b]	1,085 (1.73%)
Generator working at the time scheduled	87%
Diesel consumption (l)	22,960
Specific fuel consumption (l/kWh produced)	0.366

[a] Electricity put in the grid does not account for losses in transmission and distribution.
[b] Excess electricity refers to electricity produced that does not match with the consumption pattern and is lost.

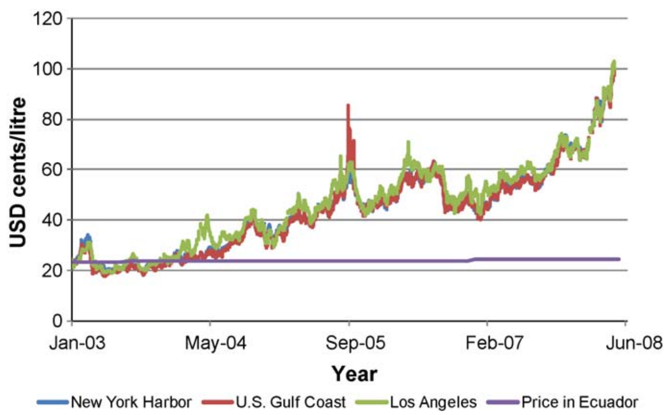

Fig. 3. International market diesel prices versus the subsidised price in Ecuador from January 2003 to June 2008 values in $/l constructed based on reported values by PetroEcuador [43] and the Department of Energy of the US [44].

$C_{ann,tot}$ is the total annualised cost of the mini-grid ($/year); $E_{prim,AC}$ is the AC primary load served (kWh/year); and E_{def} is the deferrable load served (kWh/year).

The LCOE calculated includes the costs of the distribution grid, capacity building and coordination.

Data uncertainty due to the use of different sources was included in the calculations (error bars in graphs). The uncertainty ranges include the different retrieved values for capital costs (variability in prices from the sources consulted), the differences in diesel genset lifetimes, Operational and Maintenance (O&M) costs of the generator, fuel efficiency of the generator, and diesel prices (between subsidised and market prices).

Under the current scheme the deficit created between the tariff paid by the users and the real cost of operating the generator is covered by government funds. To determine the total annual subsidy for operation and maintenance ($/kWh), $S_{O\&M}$, the following equation was used:

$$S_{O\&M} = LCOE - T_{user}$$

T_{user}: annual sum of tariff paid by the users ($/kWh).

Moreover, the subsidy to diesel ($/kWh) is determined by the difference between its market price (1.02$/l)[5] and its retail price in Ecuador (0.24$/l), being near to 1460$ M in 2007 [42]. Historical development of diesel market prices and subsidised price maintained in Ecuador are presented in Fig. 3.

When introducing PV into the diesel mini-grid there is a reduction in the consumption of diesel used to produce the same amount of electricity. To determine the indirect savings caused by the introduction of PV we calculated the annual subsidy to diesel (in $/kWh), S_d, with:

$$S_d = (D_{mp} - D_s) \times SFC$$

D_{mp}: market price of diesel ($/l); D_s: diesel subsidised price ($/l); SFC: specific fuel consumption of the generator (l/kWh).

The LCOE of the electricity produced by the diesel generator under average conditions including subsidies for fuel (0.384$/kWh) was broken down by the annualised costs for each component. The LCOE calculated with diesel market prices, with subsided diesel prices and the LCOE reported by the local ESCO EMELORO[6] are detailed in Fig. 4a. Fig. 4b depicts the subsidies per kWh ($/kWh) given to cover the deficit of the diesel and of the O&M.

4.2.1. Environmental considerations

As a signer of Kyoto, Ecuador has committed to the reduction of 5% of its CO_2 emissions, but this has not been achieved due to the lack of installed renewable energy sources in Ecuador and the constant increase in energy demand every year [36]. For this reason the new National Development Plan 2007–2015 of Ecuador proposes the need to develop an answer to the effects of climate change through actions of prevention, reduction and mitigation. The government is committed to make a transition from fossil fuel burning technologies to renewable energy sources.

The share of CO_2 emissions from the diesel mini-grid system in Costa Rica Island, 60 tonnes of CO_2 per year (see Fig. 5), is insignificant if we compare it to the total CO_2 emissions in Ecuador coming from thermoelectric generation, approximately 6.13 million tonnes of CO_2 in 2007 [36]. Nevertheless, the per capita yearly average tonnes of CO_2 emissions for Ecuador are 0.5[7] considering only electricity generation, 1.8[8] when including transport, industry and other [45]; while for Costa Rica Island the per capita emissions from electricity generation are 0.3 tonnes of CO_2 per year (with a 7 h/day service), and up to 0.91 (if we where to consider a 24 h/day service).

Even if emissions in remote regions are limited, it is crucial for developing nations to find resources and concentrate efforts into low carbon renewable energies to boost development, where energy demand is growing faster than elsewhere [46]. The idea is to seek for a different road of development, a more sustainable pathway, and through the implementation of renewable energies in off-grid areas decrease the rate of increase of future GHG emissions from developing countries [45]. For this reason, the promotion and support to introduction of renewable energy technologies in isolated regions is crucial.

Apart from GHG emissions, there are high risks and negative environmental impacts attached to maintaining diesel generators in isolated communities. The communities of the case studies are located in extremely rich biodiversity areas. The main environmental risk link to a diesel mini-grid is the transportation of oil along biodiversity rich areas, such as the Ecuadorian Amazons, where spills can have tremendous irreversible negative effects. Costa Rica Island forms part of one of the top 25 biodiversity hot spots of the world, Tumbes-Choco-Magdalena[9] [47]. While, next to

[5] The diesel market prices values from May 2008 (130$/barrel), published by the Department of Energy of the United States [43], were used as an alarming situation, although prices have decreased in recent months, the peak value of 2008 represents the situation of a highest case scenario for diesel prices.

[6] Cost of generation reported by EMELORO is lower since depreciation costs are not included.

[7] It is 16 times lower than the average emissions of 7.8 tonnes of CO_2 per capita per year from the electric power sector in the US.

[8] It is 11 times smaller than the average total emissions of 20.14 tonnes of CO_2 per capita per year in the US, and less than half of the world average, 4.37. CO_2 emissions in Ecuador are less than <1% of the total in the world [36].

[9] Extends along the eastern coast of Central and South America, from southern Panama to Northern Peru.

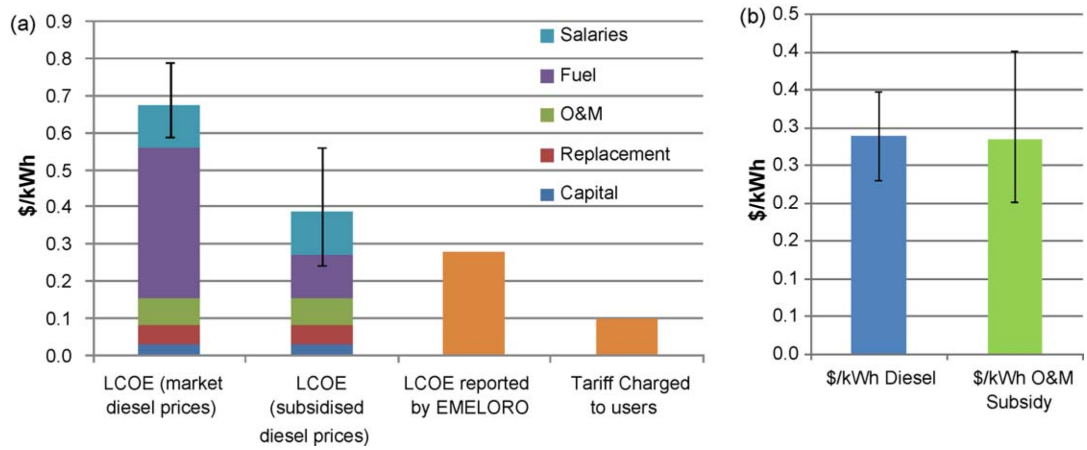

Fig. 4. (a) LCOE break-down for subsidized and market diesel prices with uncertainty ranges and LCOE reported by the local ESCO, versus the tariff charged to users; and (b) estimation of diesel and O&M subsidies required per kWh for diesel-based electricity generation in Costa Rica Island.

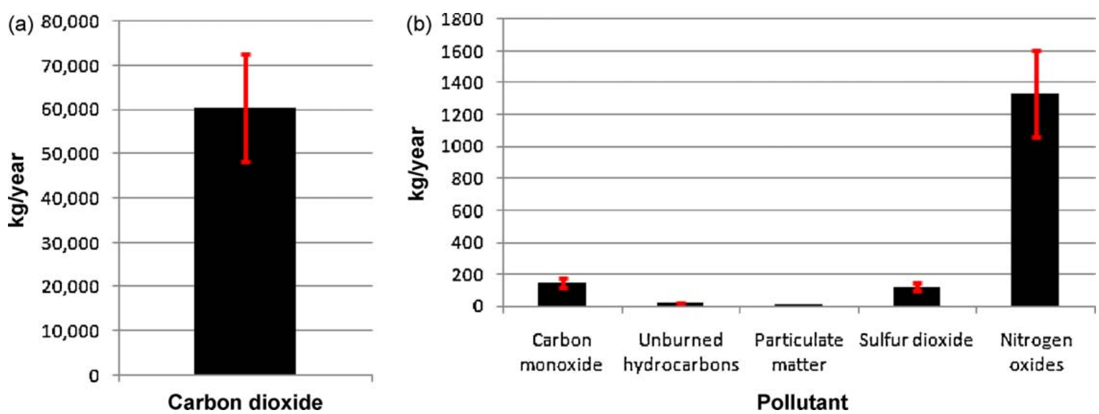

Fig. 5. (a) Yearly CO_2 emissions from the diesel generator in Costa Rica Island and (b) other yearly pollutants emissions from the diesel generator in Costa Rica Island (HOMER output).

the Nuevo Rocafuerte community (analysed for the introduction of a PV/diesel hybrid) lays the Yasuní National Park which is considered one of the most biologically diverse regions in the world [48]. The preservation of these areas should be reason enough to concentrate and channel efforts towards introducing environmentally friendly solutions, such as renewable energy technologies. Hence, reduce the environmental risk attached to diesel transportation. This, to avoid events as the one occurred in 2001 in the Galapagos Islands, spilling almost 300,000 l of fuel in the archipelago, which caused a transcendental destruction of the ecosystem, habitat alteration and irreparable damages to nature, as reported by the Charles Darwin Foundation [49]. If an economic values needs to be given, the total proposed compensatory restoration measures costs were calculated at over 9$ million by [50], total costs due to the spill of 19–27$ million[10] by [51], and the environmental risk of diesel transportation to the islands has been calculated at 0.09$/l [51].

A similar incident occurred in 2007, when a small fleet carrying 10,000 gallons of diesel for Nuevo Rocafuerte (in the Ecuadorian Amazon) was carried away by the river current producing significant environmental effects and leaving Nuevo Rocafuerte with a limited electricity-service for more than 2 months. Unfortunately, this mishap did not receive the attention it deserved by media, government, NGOs, or others.

[10] If opportunity, image, and reposition costs are considered.

4.3. A new alternative: PV/diesel hybrid system

A PV/diesel hybrid mini-grid is suggested as an alternative to the limited services offered by the current stand-alone diesel generator in the Costa Rica Island community. The alternative is to not only include renewables in the generation but also to improve the service. Three different fractions of PV-sizing are considered for the hybrid system designed to serve the community 24-h per day. The three different configurations (low, medium and high PV capacity proportion) allow us to evaluate three scenarios for the application of the RPT scheme.

4.3.1. Primary load

The average electricity demand curve of the whole province of El Oro is the baseline to extrapolate a 24-h demand curve for Costa Rica Island (see Fig. 6). In the presence of a 24-h service consumption patterns vary, where peak loads would come at later hours and consumption increases during the day.

4.3.2. Optimising the PV/diesel hybrid system

The inputs used to estimate the lifecycle cost of the hybrid system by HOMER are the capital costs of the generator, the PV system and its balance of system (BOS), controllers, batteries, inverters, and regulators, the replacement costs, and the operation and maintenance, see Table 4. The information was derived either from previous projects in Ecuador, or information from manufacturers and providers (for further details on the values see Solano-Peralta [52]).

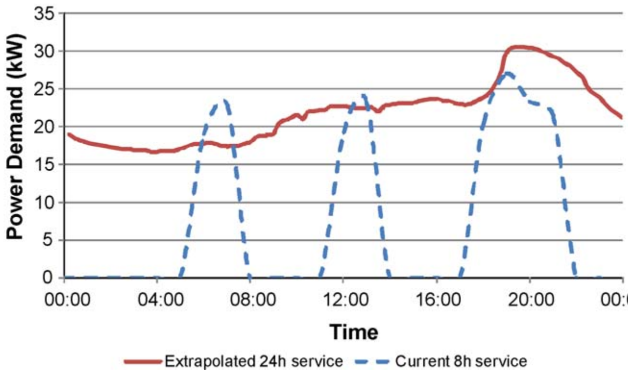

Fig. 6. Extrapolated demand curve for a 24 h electricity service for Costa Rica Island using values from the average consumption patterns of the El Oro province.

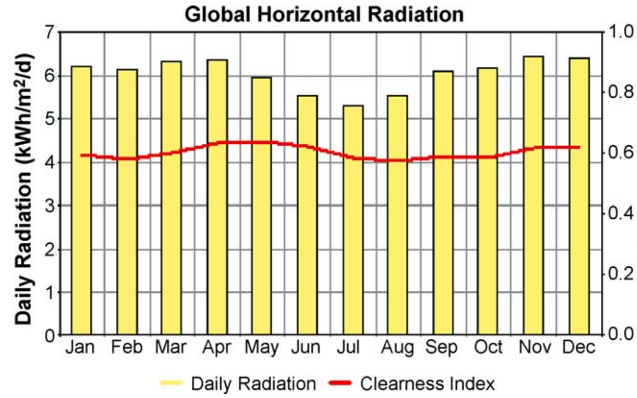

Fig. 7. Global solar irradiation for Costa Rica Island taken from NASA database (Database available at: http://eosweb.larc.nasa.gov/sse/).

Table 4
Summary of assumed capital costs for the different components considered for the PV/diesel MGS.

Components	Size Range (kW)	Cost Range ($/kW)
Diesel generator	0–100	400–800
	100–200	200–400
	200–500	100–200
PV + BOS	0–25	5250–8500 ($/kWp)
	25–100	4900–8100
	100–200	4700–7900
Batteries		170–280 ($/kWh)
Inverter		400–2000 according to size
Coordination and capacity building		10–20% of the total investment
Distribution grid		5000–10,000 ($/km)
Salaries		3000–5000 ($/person)

Coordination and capacity building are inherent to RET projects, training within the communities to manage and operate the system as well, to train the whole community on energy savings and efficiency is a crucial factor to divulge the project and to fully involve the local community.

A summary of the assumptions made can be seen in Table 5 (for further details see Solano-Peralta [52]).

4.3.3. Hybrid configurations

The optimisation of the hybrid system obtained with the range of technical characteristics mentioned above determines the boundary where the LCOE of the PV/diesel hybrid configurations are lower than the LCOE of the stand-alone diesel generator (Fig. 8). From the hybrid optimised configurations three different PV fractions in the total capacity of the system were considered, low ~30% PV, medium ~60% PV and high ~80% PV. Table 6 presents the range of LCOE values including replacements and O&M for the different hybrid system configurations proposed under low, average, or high assumptions.

When calculating the LCOE including highly subsidised fuel, the configuration with the lowest LCOE is the stand-alone diesel generator (light grey in Fig. 8a). However when looking at the LCOE with diesel market prices (dark grey column in Fig. 8a), the different hybrid system configurations appear as cost-effective alternatives. Fig. 8b shows the components' costs break-down of the different systems with unsubsidised diesel; we can clearly see

Table 5
Assumptions for the PV/diesel hybrid configuration.

	Assumptions
PV	PV lifetime: 25 years; slope: 10°; derating factor[a]: 85%; ground reflectance: 20%; no tracking system is considered
Solar resources	According to data from NASA, the solar irradiation in Costa Rica Island is quite high, reaching a daily average of 6 kWh/m^2 (see Fig. 7). An average of 5.4 PSH (10% less) is also considered due to the uncertainty in the data retrieved from NASA's website through HOMER
Batteries	Sandia National Laboratories [53] and project developers in Ecuador recommend 2–3 days of autonomy for hybrid systems. To decide the amount of batteries the following calculation was used: $B = \frac{PV_g \times D}{I_{eff} \times B_C \times DoD}$ (12) where #*B*: number of batteries required; PV_g: daily electricity generated by PV (kWh/day); *D*: days of autonomy desired; *DoD*: allowed depth of discharge (80%); I_{eff}: inverter efficiency (95%); B_C: capacity of the battery (Ah*V or kWh)
Inverters	The size of the inverters must be enough to handle the off-peak load plus 20–30% of excess capacity; hence several sizes are tested in HOMER to find the most appropriate configuration. Off-peak load is usually 20–30% of the peak load
Capacity building	There is a need to do capacity building in the community where the RE project will take place. People must be familiarised with the characteristics of having a RET feeding electricity into their isolated grid in order to sponsor an energy savings culture
Coordination of the project	There is a need for coordination of the project, starting with a feasibility study and further planning, transportation, and direction of the construction. Optimistically, in the case studies it was assumed that capacity building and coordination costs are 15% of the total investment
Distribution grid	The cost per kilometre highly depends of the terrain through which the grids have to be extended. The losses on the distribution grid are already included in the primary load, which should range between 10 and 20%, depending on the size of the grid. In the case studies distribution is made at medium tension. An option for lowering the losses would be to make the grids in low tension [25]
Other considerations	Replacement costs for batteries and inverters are expected to remain similar, since technologies are already mature. For the PV + BOS components, in order to deal with uncertainty on the collected data we assume a variation of ±25% (according to the different costs reported in projects inside Ecuador and information gathered from different manufacturers), to see the effects of attaining lower costs for the renewable part, and higher costs in case values were underestimated.

[a] To account for temperature and reflectance losses, efficiency drops in time and other systems losses.

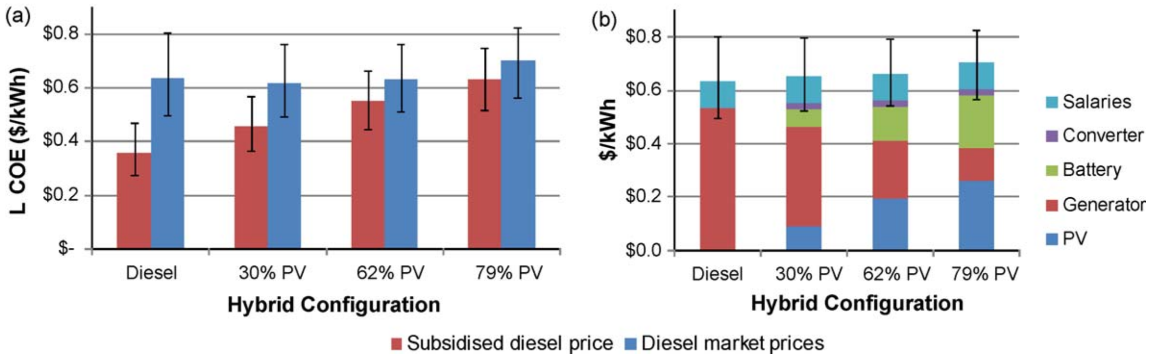

Fig. 8. (a) LCOE for the different PV scenarios compared to the diesel generation system with "dispersibility" bars indicating low and high component costs assumptions. (b) LCOE break-down of the different hybrid system components using diesel market prices.

Table 6
LCOE values for different PV penetration scenarios in the hybrid system in Costa Rica Island considering diesel subsidised prices.

PV fraction in the 110 kW hybrid system	LCOE ($/kWh)		
	Low	Average	High
0%	0.28	0.36	0.47
30% (32 kWp)	0.37	0.46	0.57
62% (68 kWp)	0.45	0.55	0.67
79% (90 kWp)	0.52	0.63	0.75

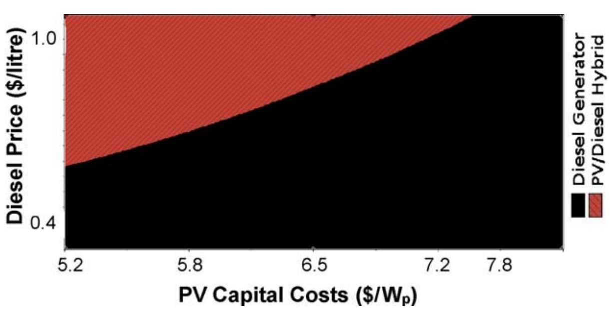

Fig. 9. Optimal system according to different diesel prices considered and PV capital cost multiplier for Costa Rica Island.

the high costs attached to the diesel generator (due to fuel and maintenance costs).

Fig. 9 (calculated by HOMER) depicts the boundary where hybrid systems become a cost-effective alternative for Costa Rica Island, which is dependent on the diesel prices and the PV capital costs. The boundary is shown when diesel prices are higher than 0.6$/l and PV capital costs range between 5.2 and 7.2$/Wp.

The inclusion of capital costs for distribution grid and capacity building and coordination activities (CB & CO) raise the LCOE between 10 and 20% (Fig. 10). The LCOE for the diesel generator ranges from 0.3 to 0.5$/kWh (Fig. 10a) when considering subsidised diesel prices, and can reach 0.9$/kWh if we consider the highest life-cycle costs with diesel market prices (Fig. 10b). The hybrid configuration with 79% PV fraction ranges from 0.6$/kWh (lower life-cycle costs with subsidised diesel price, Fig. 10a) to 0.92$/kWh (higher life-cycle costs with diesel market price, Fig. 10b), showing a lower uncertainty in the cost ranges.

4.4. Economic analysis for the optimisation of the RPT values

To study the broad potential of the new scheme, we optimised the financial set-up under three different profitability outlooks:

(a) non-profit scenario; considered when covering only the initial investment and O&M costs (NPV = 0),
(b) profitable, and (c) highly profitable; are considered when covering all the costs of the project and generating a profit for the owner of the hybrid system (attractive NPV > 0) resulting in Internal Rate of Return (IRR) 8 and 12% for profitable and highly profitable, respectively.

The RPT values are determined for the three profitability scenarios considering the different hybrid configurations optimised in the previous sections.

In the previous sections we have defined the LCOE ranges for Costa Rica Island. This section provides the analyses of the following financial indicators: Net Present Value (NPV), Internal Rate of Return (IRR), and Profitability Index (PI) [54]. The determination of the different financial parameters allows us to compare and evaluate the financial viability between different set-ups. Specifically, the IRR is commonly used to measure the financial efficiency of a concrete project, the NPV provides useful information when a project is aimed to be profitable or neutral, and

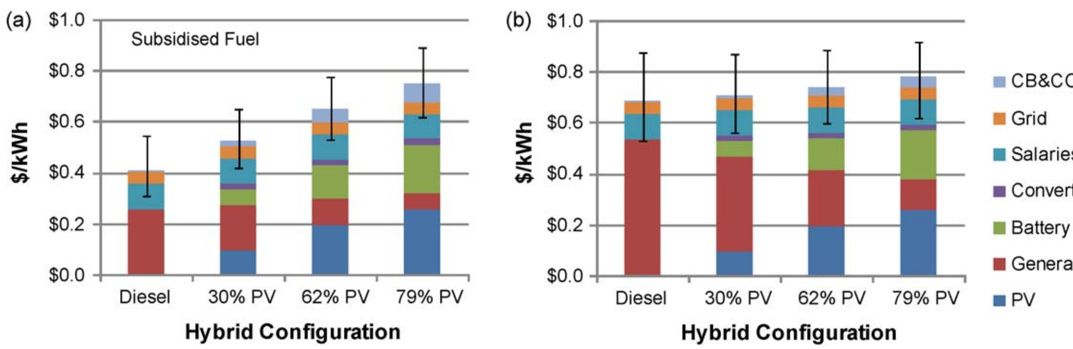

Fig. 10. (a) LCOE including the distribution grid, capacity building and coordination of the project using subsidized diesel prices for Costa Rica Island and (b) with diesel market prices.

the Profitability Index indicates financiers how fruitful their investments might be.

The NPV determines the total summation of cash flows for a long-term investment:

$$\mathrm{NPV} = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t}$$

N: total time of the project; t: time of the clash flow (years); r: discount rate; C_t: net cash flow at time t.

To determine the IRR, the value of the discount rate is calculated when NPV equals to zero:

$$\mathrm{NPV} = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t} = 0$$

and the Profitability Index, PI, refers to:

$$PI = \frac{FCF_{PV}}{II_{PV}}$$

FCF_{PV}: future cash flows present value; II_{PV}: present value of the initial investment.

Many of the already existing isolated MGS do not generate a profit because are installed under subsidies and as development projects by governments or other non-profit organisations; consequently the cases studies are analysed under a non-profit approach. In most of the off-grid communities with mini-grids in Ecuador (and most Latin America countries) the systems are ran by a private energy distributor although they are not generating a profit. This particular situation is accepted in Ecuador, due to the fact that electricity is considered as a right for all Ecuadorian citizens; hence the government is in accordance of funding the losses of these systems to the private energy distributors.

To calculate the RPT value required for supporting the renewable electricity produced under a non-profit perspective, NPV = 0, the following equation was used in each optimised hybrid system configuration:

$$\mathrm{NPV} = I_{inv} - \sum_{t=0}^{n} (RPT_y + E_{rev}) - (O\&M) = 0$$

I_{inv}: initial investment ($); RPT: yearly sum of Renewable Energy Premium Tariff ($/year); E_{rev}: annual revenue from electricity tariff charged to users ($/year); $O\&M$: yearly operation and maintenance costs ($/year); n: lifetime of project (in years).

The yearly RPT is calculated by:

$$RPT_y = PV_{eg} \times RPT$$

PV_{eg}: annual amount of electricity generated by PV (kWh/year); RPT: Renewable Energy Premium Tariff ($/kWh).

$$ER_{rev} = E_{tot} \times T$$

E_{tot}: total electricity generated by the MGS; T: tariff set to users.

This paper analyses profitable approaches for governments that aim to increase private investment in renewable energy projects. The same methodology was used for a profitable perspective taking an NPV > 0 and an IRR = 8 or 12% for highly profitable perspective.

As mentioned, the previous section analysed three different configurations depending on the PV shares (low, medium and high) of the total hybrid system capacity. The two higher PV fractions are analysed to determine if there are major differences between their LCOEs.

The error bars considered for the hybrid systems are based on all the costs, since the RPT value seeks to cover the whole system. The ranges in prices clearly could affect the value determination of the RPT.

4.4.1. Scenario 1: 31% of PV fraction of the total hybrid system capacity

In the 31% PV penetration (low share) configuration the RPT value is optimised to recover solely the investment in the RET without including the diesel generator investment and to continue receiving the governmental subsidy that covers the O&M of the diesel generator.

Isolated regions that already have a diesel genset in operation would adapt more easily to the configuration with 31% of PV. The introduction of a PV fraction into the stand-alone diesel system will reduce operation costs and diesel consumption, and at the same time will include a peak shaving on the electricity consumption.

The best straightforward option for the adaptation of the ownership of the entire MGS to the new scheme is when the current operator (either private, ESCO or municipality) invests on the new integrated PV system. This option will avoid having two different entities in charge of the system. For the ownership and institutional framework, the simplest mode to adapt to the new scheme is that the PV owner receives annually or monthly the total RPT amount in accordance to the total kWh produced by the PV likewise.

The RPT has been calculated to cover the PV section: the salary of one technician, plus all costs related to the replacement of batteries, PV modules, inverter, controller, capacity building and coordination of the project. The costs of the diesel generator (fuel, O&M, and technicians) are not included in the cash flows.

Under a non-profit perspective with 6% recovery of the PV investment, a RPT value of 0.66$/kWh provides a viable alternative to the current diesel genset with a neutral Profitability Index (PI = 1) (see Fig. 11a).

The introduction of the PV hybrid system under the RPT award will encourage the operator to minimise the use of the diesel generator. This alternative decreases the inefficient diesel genset operation which requires keeping the current subsidy on the deficit of operation, and creates a higher interest in introducing PV into the existing diesel system in order to receive the RPT value.

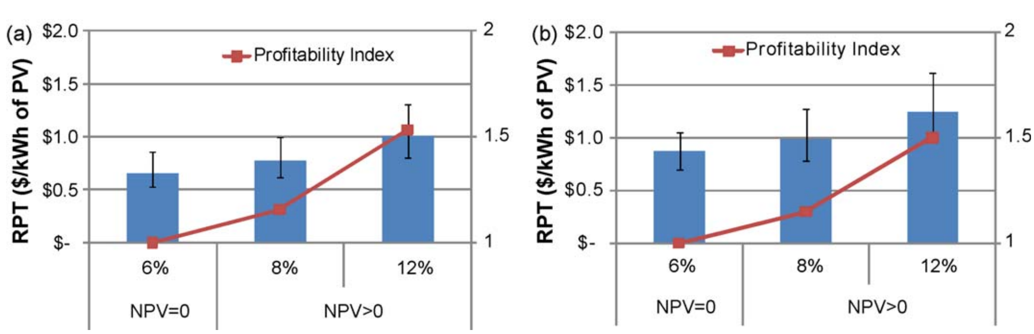

Fig. 11. RPT values ($/kWh) for NPVs with different IRR (%) and their respective Profitability Index in Costa Rica Island hybrid system for (a) 31% PV fraction and (b) 62% PV fraction.

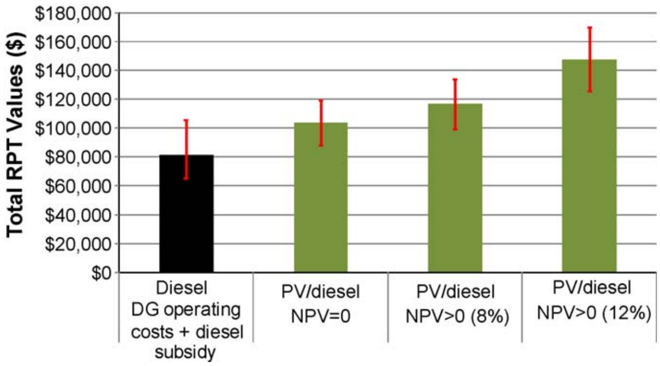

Fig. 12. Diesel generator (DG) operating costs ($/year) plus diesel subsidy 'saved' due to introduction of 62% RE fraction compared to annual RPT amount for the neutral and profitability perspectives considered (IRR = 6, 8, and 12%).

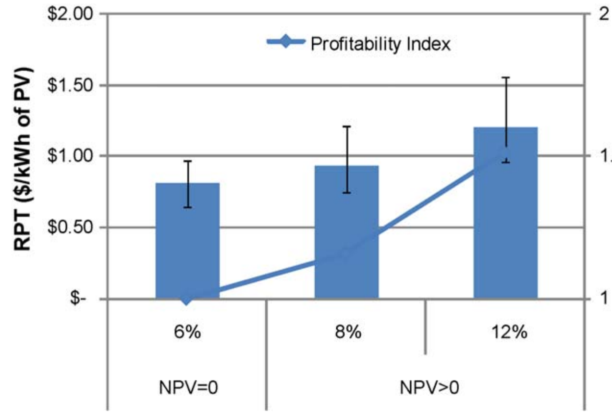

Fig. 13. RPT values ($/kWh) for positive NPVs with different IRR (%) values and the respective Profitability Index value for a 79% RE fraction in Costa Rica Island.

4.4.2. Scenario 2: 62% of PV fraction

In the hybrid systems with 62% (medium share) and 79% (high share) PV fractions the RPT values is determined to cover the investment and operation of the whole hybrid system.

For a higher PV penetration with higher capital costs, the hybrid system is analysed as a co-generation plant, where the diesel is a back-up utility. In the case of having a medium PV penetration (~60%) with 68 kWp of PV, the RPT values obtained are higher since the revenue covers the losses from the other 40% of the electricity produced by the diesel generator. The owner of the hybrid system obtains a premium tariff for 60% of electricity produced by the hybrid system, then an RPT of 0.93$/kWh is required to recover the investment on the hybrid system with a neutral revenue, NPV = 0 (see Fig. 11b) when we consider the current average user tariff in Ecuador of 0.10$/kWh.

Fig. 12 depicts that for a non-profitable scenario, the RPT expenditure (second left column) is similar to the current sum of subsidies given for O&M losses of the diesel-based electricity generation with 24 h service to the community (first left column).

Since the RPT value is calculated to cover all the expenses of the MGS, i.e. capital costs, coordination, operation and management, the same expenses have been included for the diesel generator.

The annual RPT expenditure is expected to be a 25% higher than the generator's current subsidies for 1 year (Fig. 12), when we compare the average values. While, if we consider the upper value of the given subsidies for the operation of the generator, their cost is higher than the average RPT expenditure required to achieve an NPV = 0. The difference between the expenditure on the RPT for the hybrid system and that for diesel generator is expected to be turned because the expenditure on the diesel generator is likely to continue increasing while the hybrid systems costs are expected to be reduced. This is due to the fact of expected reduction of PV costs, expected to gradually arrive at $1.3/Wp by 2030 [55].

4.4.3. 79% PV fraction

RPT values for an NPV = 0 and NPV > 0 for this PV/diesel hybrid configuration is still quite high, 0.81$/kWh up to $1.2 in the most profitable case (Fig. 13). In the case of having a high PV fraction of ~80%, i.e. 90 kWp, the RPT values are expected to be quite high as well, due to the large investment that has to be made for the PV. Values are close to the previous situation, since the former one has high operation costs and deficit from running the diesel genset a larger % of time, while this one has higher investment costs.

Values obtained for the RPT are not exorbitant if compared to the current Feed-in Tariff values in Europe (e.g. 0.75$/kWh in Italy) also considering that users pay up to 0.30$/kWh and that the systems are grid-connected (not requiring a back-up system). Nevertheless, for Ecuador the RPTs calculated are a bit far from the current offered values by the government (see Table 1). This underlines the necessity to concentrate efforts to reduce costs of projects, have the support from international organisations, give tax exemptions and promote the local manufacturing of renewable technologies.

4.4.4. Achievable values: looking at the lowest life-cycle costs

When considering optimistically the lowest life-cycle costs of the PV hybrid system, the optimised RPT value can decrease by 20%. Moreover, if we consider 10% of the total investment for the capacity building and coordination of the project, and the distribution grid, as public property, to be covered by the government the RPT value optimised for a neutral revenue (NPV = 0) is 0.59$/kWh and 0.57$/kWh for 62 and 79% PV fractions, respectively. These values are close to the current Feed-in Tariff values, 0.52$/kWh, for PV installed in mainland of Ecuador.

Fig. 14 presents a more positive scenario, where for a non-profit approach, RPTs are lower than 0.60$/kWh. Even in the most profitable approach the RPT required does not reach 1$/kWh. As well, when we consider the lower life-cycle costs of PV the expenditure per year in RPT (for an NPV = 0) is lower than the current necessary subsidies given by the government directly (FERUM funds) and indirectly (subsidy to diesel) to maintain the genset running in Costa Rica Island (see Fig. 15).

The lower life cycle costs of PV make the RPT a very attractive alternative, where only a shift of funds is required, from financing a fossil fuel technology to the support of a renewable energy technology.

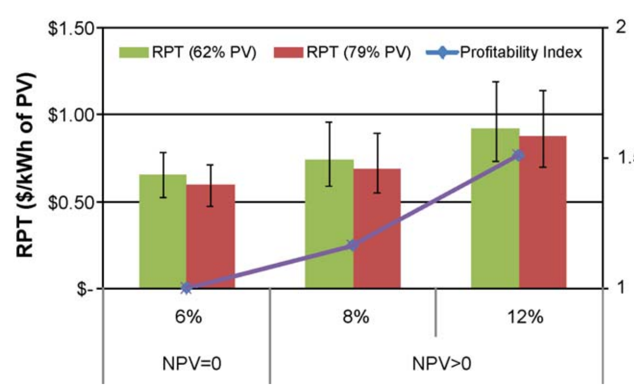

Fig. 14. RPT values ($/kWh) for neutral and profitable scenarios (with IRR = 8 and 12%) and the respective Profitability Index value for a 62 and 79% PV fraction under the lowest life-cycle costs.

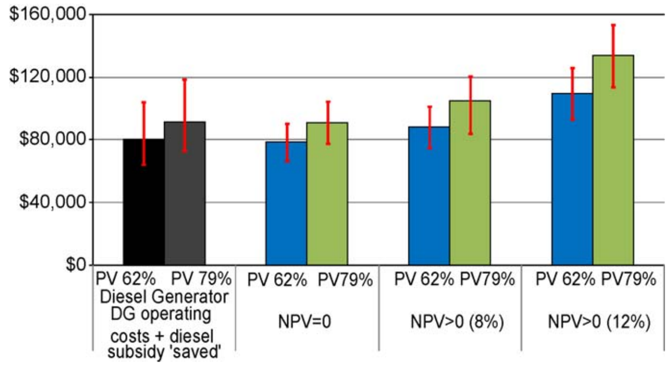

Fig. 15. Comparison between channelling of funds to the diesel electricity generation versus RPT annual expenditure with a 62 and 79% PV fraction (including uncertainty) in Costa Rica Island.

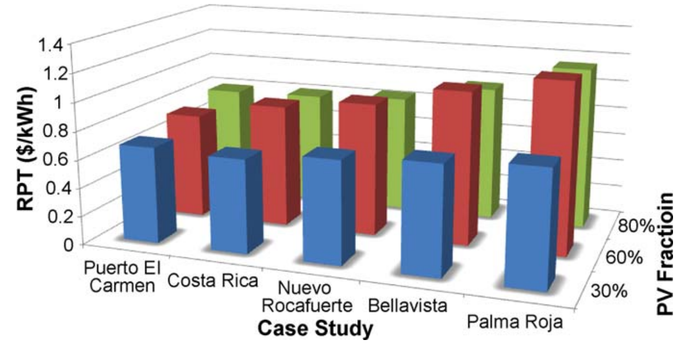

Fig. 16. RPT ($/kWh) average values for all case studies for the different PV fractions considered (non-profit approach).

4.5. An alternative scheme for isolated mini-grids in Ecuador: broadening results

The analysis of a larger number of existing diesel mini-grids in isolated communities with different demands allowed us to evaluate the adaptability of the scheme and to generalise the necessary conditions of the scheme. The location of the evaluated mini-grids is an important variable with differences in access to the communities, solar irradiation and electricity consumption patterns. The case studies were selected according to the availability of information, distance from the grid, the limited electricity service of the current diesel mini-grid, the high operation and maintenance costs of current system, size of the system, and the feasibility for the adaptation of the current diesel generator to a PV/diesel hybrid.

Conclusions and recommendations will be based on a further range of pilot cases and they are the bases for defining an appropriate RPT value. Still, each project retains its uniqueness and it is expected to serve only as considerations and recommendations that can be useful for other cases.

Table 7 includes social indicators for each community contextualising their social situation. It gathers the main characteristics of the current generator installed in each of the case studies and the LCOE under the different proposed hybrid system alternatives.

The largest system analysed is in Palma Roja which serves 752 users (with a 500 kW generator), while the smallest community is in Palma Roja with only 17 users (with an 80 kW generator, while the smallest generator is in Bellavista Island, 45 kW). The Nuevo Rocafuerte community, in the middle of the Ecuadorian Amazons, is more than 200 km away from the grid, while Costa Rica and Bellavista Islands of the Jambeli Archipelago are 15–20 km away from the mainland. Average solar irradiation varies considerably between the case studies, from 4.08 kWh/m^2/day in Palma Roja up to 6.05 kWh/m^2/day in the islands of the Jambeli Archipelago. Detailed analysis from Bellavista Island, Nuevo Rocafuerte, Palma Roja and Puerto El Carmen case studies can be found in Solano-Peralta [52].

From the previous table we can see the variability of the LCOE in the diesel generators from 0.21 to 1.17$/kWh, depending on the system and location. The values for the hybrid systems, vary from 0.33 to 0.94$/kWh, depending on the PV fraction introduced and the location of the project. It must be noted the high LCOE in Palma Roja which is mainly due to the over-dimensioning of the generator operating in this community.

Fig. 16 presents a summary of all the calculated average RPT ($/kWh) values in each case study, for the different PV fractions considered.

Fig. 17 depicts the calculated RPT values for a profit-oriented approach with an IRR of 8%.

5. Benefits and disadvantages of the PV/diesel hybrid versus stand-alone diesel systems

From the analysis, research and observations based on the studied cases, we summarize the main environmental and social

Table 7
Case studies summary along with social indexes.

Town	Nuevo Rocafuerte	Bellavista	Costa Rica	Palma Roja	Puerto El Carmen	National average
Province	Orellana	El Oro	El Oro	Sucumbíos	Sucumbíos	
Region	Amazons	Coast	Coast	Amazons	Amazons	
Extreme poverty index[a] (% of population)	39.3	51.4	51.4	59.1	44	31.9
Illiteracy rate (%)	4.6	5.5	5.5	12	7.9	9
Un-employment rate by province (%)	5.1	5.1	4.4	5.1	5.1	6.7
Healthcare offer index (from 40 to 100)[b]	45	40	40	42.2	54.2	49.2
# of MGS users	110	52	65	17	752	3.3 million
Current generator size (kW)	170	45	55	80	500	
Current electricity service (h/day)	15	7–8	7–8	7	19	
LCOE with subsidised diesel ($/kWh)	0.32	0.47	0.38	1.17	0.21	0.06[c]
LCOE with diesel market price ($/kWh)	0.63	0.80	0.64	1.45	0.58	
Distance to grid (km)	200–250	15–20	15–20	60–80	80–100	
Average solar irradiation (kWh/m^2/day)	4.35	6.05	6.05	4.08	4.35	4–5
LCOE PV ~30% ($/kWh)[d]	0.42	0.55	0.46	0.68	0.33	
LCOE PV ~60% ($/kWh)	0.55	0.63	0.55	0.84	0.45	
LCOE PV ~80% ($/kWh)	0.64	0.70	0.63	0.94	0.54	

Source: Sistema Integrado de Indicadores Sociales del Ecuador (Integrated System of Social Indexes from Ecuador, SIISE [56]) database and Solano-Peralta [52].
[a] Based on unsatisfied basic needs: indicators defined by province.
[b] Base on # of doctors, nurses, dentists and obstetricians per 10,000 inhabitants and healthcare facilities. The index goes from 40 to 100.
[c] Average electricity price in the Wholesale Electricity Market (MEM) in 2007 in $/kWh Reported by CONELEC.
[d] Without subsidy to diesel.

Table 8
Benefits and disadvantages of stand-alone diesel generators versus PV/diesel MGSs.

Diesel Generators	PV/diesel MGS
Benefits	
Low/moderate initial investment costs	It can ensure a more stable LCOE and avoid increases in the future COE due to rising diesel prices
Easy to introduce and limited knowledge required for its maintenance (although a lot of work)	PV/diesel MGSs are a good approach for electrification of isolated regions that are sparse and have a medium ('urban') energy demand, technologies complement each other
It has been the only alternative to electrify some isolated regions	They can deliver a lower LCOE than SAS and give a high-quality service of electricity and enhance further the social and productive activities of the communities
In case of lack of funds or problems, the generator is just shut-down	It can have a relatively rapid introduction when financing is available, due to the ease and flexibility of the technology
Cost of electricity is lower when systems benefit from diesel subsidies	It is noise and pollution free
	Low operation and maintenance costs
	PV and diesel are complementary technologies and can offset the other problems
	When considering current diesel market prices a PV/diesel MGS becomes a better alternative in most circumstances
Disadvantages	
High operation and maintenance costs	Not adequate for disperse communities
It must benefit from subsidies to diesel, and O&M	There are few previous running MGS projects
Gives a limited quality service, constant break-downs	High capital costs
People are not interested in controlling their energy consumption	The COE of diesel generators becomes more economical than of PV/diesel hybrid (with a PV fraction of more than 50%) when capacities larger than ~100–200 kW[a]
It can suffer from significant operational problems and leave communities without access to electricity for months	
The diesel dependency limits the service and quality of life of users/clients	

[a] According to various sources and results from this study.

benefits and disadvantages when swapping from and stand-alone diesel system to a PV/diesel hybrid system (see Table 8). Among the social benefits that a PV/diesel hybrid system incurs, two key significant factors are that the security of electricity supply will be increased and the community will be less dependent on the difficult access to diesel to power their town. Renewables can give an 'autochthony' and independence from fossil fuels. Health risks to operators of the diesel generators and noise are reduced and the right to proper access to electricity will increase the life quality of the communities. Proper access to electricity allows for further productive uses, introduce new activities (e.g. tourism), and better services (e.g. telecommunications, health care, and social activities). On the other hand, there can be negative effects similar to an urban energy path consumption, dependency on project developers, and distrust due to few previous project failures. Looking at the environmental benefits, we can mention the reduced transportation risks of diesel, avoidance spills, reduction of GHG emissions from the generator, and diminished indirect effect to biodiversity rich regions. Bringing electricity to communities that lacked it spawns opportunities for development and can generate an important effect on creating jobs, plus the reduction of environmental and health external costs of fossil fuel based electricity. Nevertheless, it is important to dispose properly batteries and other components that can have negative effects on the environment if mishandled. Other more general attributable benefits to the inclusion of renewable energies in the Latin American context are presented by Coviello [57].

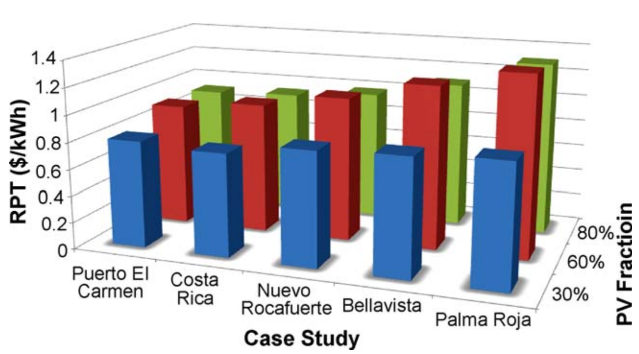

Fig. 17. RPT ($/kWh) average values for all case studies for the different PV fractions considered (profit approach for an IRR = 8%).

A cost-effectiveness comparison between the current mechanisms that cover the initial investment versus the RPT scheme is not presented, since no projects under the RPT scheme have been developed so far. Nevertheless, it is assumed that by channelling funds towards the electricity produced can be a more effective way than funds to electricity projects, as has been the experience with FiTs.

6. Conclusions

Even if mini-grids based on renewable hybrid systems have been considered and are accepted solution for off-grid areas, their inclusion has been 'reserved' so far. They have proven the achievable benefits, but due to a limited amount of experiences there is still room for progress in their dissemination. In addition, initial investment costs although already effective in some cases, remain high.

PV/diesel hybrids are in a continuous technical improvement, where more acquaintance with the technology is required to perk up the operation of the systems. The know-how needs to be broadened and outcomes need to be shared to seek optimal solutions. There is a need to foster their implementation and seek for mechanisms that can take them where there are most needed.

The RPT scheme seeks to encourage the introduction of renewables into 'grid-extension-prohibitive' sparse isolated communities and to make the transition from diesel generators to renewable hybrid systems easier and more accessible. The scheme looks for long-term sustainable projects instead of the common short-term diesel-based generation solution promoting a shift towards cleaner technologies. Nevertheless, the RPT scheme results in a multifaceted approach due to the large number of potential considerations, variables, and externalities attached to its implementation. The new RPT approach is complex, since it requires a country/region specific analysis and constant check-up of the renewable electricity produced.

The following table summarizes the conclusions for the specific analysis of the cases studied in Ecuador.

Grid-extension

- Investments in large-scale hydropower have been limited in the last years, limiting the extension of the grid in the Amazons.[11]
- For the time being, grid-extension in the Amazons is not viable due to the difficult access to many regions and the negative environmental effects this could have.
- In the case of the Jambelí Archipelago, the ESCO has discarded the grid-extension due to the high costs of long cabling needed to connect the islands and the mainland.
- In the Putumayo Region grid-extension is a viable option after the province is connected to the national interconnected system. There is a time uncertainty until the national connection is finished.

Diesel-alone MGSs

- The regular interruptions of the electricity service due to lack of diesel, maintenance, or other technical problems affect negatively the communities' activities.
- The operation of diesel generators in off-grid areas requires the channelling of large quantity of funds.
- The service given to users is limited to a few hours per day and even the generators work less than 90% of the scheduled time.
- People resent the operation of the diesel generator and constantly complain about the service that is given to them. This is reflected in many delayed payments.
- ESCOs have difficulties in maintaining the diesel systems due to distances, difficulty of access, and disinterest due to lack of benefits. It rather becomes a burden to them.
- Municipalities must take a role in the operation of systems and aid the ESCO in the operation of the system in order to give a service to their community.
- ESCO, municipality and government, have to make an enormous effort to maintain the electricity service.
- There is rarely any tourism in the towns even if they have nature paradises next to them. In the Jambelí Archipelago some bird-watchers appear sporadically.
- MGS can give a closer-to-modern access to electricity, and allow the presence in isolated communities of many facilities like water pumping, clinics, telecommunications, among others.
- Social indicators rank better in the towns/localities with a MGS. Is PV going to improve this?
- A disposable energy culture is created by the diesel generator.
- There are high environmental risks attached to the transportation of diesel as seen in Galapagos. In the case of the spills in the Napo River (Amazons), negative impacts are still to be assessed.
- The current subsidy to diesel in Ecuador hides the real costs of operating diesel systems.
- Diesel generators operate quite inefficiently and electricity supply does not match the demand loads. There is a lot of excess electricity wasted.
- Uncertainty in the operation of the generator, like its efficiency, lifetime, and O&M, can have a significant effect on the COE. It is more complicated to make life-cycle costs analysis on them, since these factors can vary considerably.
- At current diesel market prices the LCOE increases two-fold, at alarming rates.
- Systems require not only the diesel subsidy, but also an O&M subsidy to cover the gap between the COE and the tariffs paid by users.
- CO_2 emissions are not significant, but other factors such as noise, health impact on the operators and the risk of diesel transportation have prejudicial effects on the environment.
- Smaller diesel system results in higher COE.

PV/diesel MGSs

- Due to high rate of electrification the potential of new MGSs in Ecuador appears to be limited, however this should be verified by updated field studies.
- Experiences in Ecuador can be useful for replications in other Latin America countries, spreading the know-how.
- Before introducing a PV into MGSs, energy efficiency considerations must take place to improve the current situation of the operating system.
- Hybrids offer a safer long-term option due to higher uncertainty of the diesel-alone systems operation: uncertainty on the generator's lifetime and the fuel efficiency; plus the likely increase in diesel prices. Hybrid systems allow a simple updating in case of increased load.
- At current diesel subsidised prices a PV fraction of 30% can already be cost-effective, looking at the lower limit of the life-cycle costs.
- At diesel market prices, even an 80% PV fraction can be cost-effective, when comparing only the technologies.
- Further reductions in the COE of PV/diesel hybrids are expected due to the learning curves of the technology versus amount of hybrid systems installed.
- In the project locations where the density of population is low or solar irradiation is lower than 5 kWh/m^2/day, the introduction of PV may still require financial assistance or further development to be cost-effective in off-grid areas. This will change when the environmental and social benefits of renewables are considered. The priority of the electrification projects do not necessarily have to be cost-dependent.
- Battery sizing of hybrid systems is an important factor to take in consideration. In some implemented projects in Ecuador the battery lifetime was much shorter than the manufacturers' specifications and/or values given by HOMER.
- The approach of introducing only 30% of PV separately seems rather complicated since PV investment would be made separately from the current MGS operating; the deficit of operation of the diesel part would still have to be covered by some entity. Attractiveness for PV introduction would be the lowest.
- The government would save indirectly a considerable amount of financial assistance, due to lower expenses in diesel subsidies and to the deficit in O&M, as has been the case in Floreana.
- The system size, solar irradiation and operation of the diesel generator (efficiency and lifetime) are determining factors of the LCOE. The PV + BOS capital costs also have a considerable effect.
- In systems smaller than 100 kW, hybrids are a more cost-effective solution than diesel-alone systems, although their life-cycle costs ($/kWh) are higher in general.
- Higher solar irradiation further benefits the introduction of PV. In case of considerable differences in irradiation values, a demarcation on the RPT values could be appropriate.
- In larger systems >200 kW, the initial investment in large fractions PV is high. This can hinder the introduction of PV in such systems (lack of funds and/or higher risks), where other options like grid-extension could be more viable.

RPT scheme

- In the cases of hybrids with a 30% PV fraction and when the investment wants to be recovered only for the PV, a renewable premium tariff is fixed for 20 years between 0.60 and 1.00$/kWh (non-profit to profitable approach).
- In the cases of hybrids with 60% and 80% PV fractions, the premium tariffs are similar to each other. The high costs of the investment for 80% PV offset the high costs of diesel-operation in the 60% case.
- The RPT values range between 0.80 and 1.30$/kWh (for 20 years) depending on the profit or non-profit approach and on the size of the system. Small systems (<100 kW) results in higher RPT values. It is clear that the current value of the FiT (between 0.52 and 0.57$/kWh) for off-grid systems in Ecuador and the period of 12 years is too short.
- In the case of 60 and 80% PV fractions, the government can divert the funds they are using for covering the deficit in O&M and 'save' the indirect subsidies to diesel.
- The total amount of annual RPT expenditures for the non-profit approach is comparable to the current amount of funds that maintain the systems.
- When taking the lowest life-cycle costs achievable for the 60 and 80% PV fractions, the hybrids are cost-effective in all situations. The RPT values decrease to 0.55–0.80$/kWh (non-profit – profit), and the yearly expenditure is lower than current diesel operation.
- The savings are higher when considering the highest life-cycle costs of the diesel generator, and under the assumption that diesel costs continue rising.
- Non-profit and profitable scenarios present a difference in the values of RPT. An evaluation must be made as to what alternative is more convenient in accordance with the government's policies.
- The government and funding agencies will determine the best approach (either profit or non-profit) to increase the effectiveness of the promotion of renewables in off-grid areas, taking into consideration the country's situation and idiosyncrasy.

[11] Ecuador is energetically strongly oil-dependent. It only takes advantage of 11% of its hydro potential, and more than 80% of all the energy consumed (electricity, transportation, industry, sectors) is fossil fuel based.

The operation of diesel-alone systems is a 'pricey headache' and requires high-subsidies, covering of the initial investment and a continuous financing of the operation and maintenance to give service in off-grid communities. The funds channelled to cover the deficits in operation of diesel-alone systems are most likely to continue increasing, creating a snowball effect. This is so due to the increase of diesel prices, and the inefficiencies and unpredictability of diesel generators.

As a solution, PV/diesel MGSs can bring benefits to remote communities, not necessarily only economical ones, but others that have positive impacts: such as social and environmental considerations. Hybrids can give a sense of independence to the community and diminish their preoccupation with electricity supply. Also, it can create an added value to the locality, e.g. initiate eco-tourism activities that bring jobs and promote new productive uses. Another step is being taken in promoting sustainable independent communities.

7. Recommendations

Electrification rates in Ecuador are high (90%) and the government reached most remote regions. Still, there are some areas being serviced with diesel gensets that could benefit from the introduction of PV/diesel hybrids. The government has made tremendous strides in the Galápagos and positive results are stimulating replication of the work in other parts of the country. The Ecuadorian government is making an exemplary effort towards the promotion of renewables by taking a forefront in defining an off-grid FiT. A step further is now necessary to make this regulation a more effective tool.

The presented analysis was made for projects established in Ecuador, and results are based on their specific political, economical and geographical circumstances. For other countries the roles of stakeholders, actions in a country, focus towards renewables might be different and conclusions taken in the previous section might have to be taken into consideration. The implementation of the RPT model is not necessarily strategically more complex than to subsidise the initial investment. The scheme is proposed as an alternative support scheme depending on the nature of the project itself and externalities that impact it and it might be not always the best option. In this case, the RPT scheme is a suitable approach when interests are towards increasing coverage and improving the quality of electricity service to off-grid areas, and when achieving the benefits mentioned in Section 5.

There are many regions in the world that share similar characteristics, where the introduction of PV into diesel grids is being studied. Specifically, studies have been conducted in the Brazilian Amazons, India, China, Argentina, among others, and shown the cost-effectiveness and attached benefits of adding PV. The results of this study show that the RPT scheme can represent a means for these countries to 'fuel' their efforts to introduce renewable energies in isolated grids and achieve further PV dissemination and bring an independent quality service to isolated areas.

1. Governments have to focus on defining a specific regulatory framework for off-grid small scale electricity generating systems; seeking to give more liberty to independent project developers, cooperatives, municipalities and NGOs that are interested in making new projects.
2. An initial step, already taken by CONELEC in Ecuador, is the adequate identification of agglomerated communities that can be served with a MGS and proper registration of all systems >1 MW installed power serving communities.
3. Positive results obtained with experiences so far can be useful to increase public acceptance and provide useful lessons learnt for future projects. As well, funds that are currently covering the deficit in operation of diesel-based electricity generation can be diverted for financing the introduction of renewable energies.
4. Due to the existence of an off-grid FiT in Ecuador it becomes easier task to properly define the regulation and seek for governmental support to create a law that can give security to project developers, it depends on the government's willingness to consider further introduce and support the new alternative scheme.
5. As recommended by the WG4-EU PV Technology [13] in its report, the long-term credibility of the funding institution that will channel the RPT is vital, the need to have a strong policy support and regulatory framework, set tax incentives and credits for renewable technologies, and seek to internalise social and environmental benefits into the realisation of renewable energy projects.
6. The inclusion and support of project developers, funding agencies and communities is indispensable. Through willingness of project developers to invest in projects; interest of funding agencies to finance projects with the RPT scheme, assuring project developers the tariff payment and define specific characteristics for the channelling of the funds.
7. Some considerations for the RPT scheme are (i) payment of tariff in accordance to made-available electricity [58]; (ii) the tariff should cover the initial investment and operation of the PV/diesel MGS; (iii) the periodicity of premium tariff payment should be fixed preferably every 6 months; (iv) provide a warranty of payment to project developers; (v) define a minimum renewable fraction that needs to be introduced; (vi) as a conclusion of this study the RPT scheme needs to be set for 20 years at values from 0.70 to 0.90$/kWh for non-profit approaches and 1.00–1.30$/kWh for attraction of private investors with a profit-oriented approach. Nevertheless, if we look at the more optimistic results of having lower life cycle costs and the absorbance of the distribution grid costs by the government the RPT values could be reduced by 0.20–30$/kWh; (vii) properly define the key parameters for setting the RPT values together with the government, where variables like solar irradiation, MGS's sizes, and location can have an effect on the life-cycle costs of the projects and need to be taken into consideration; and (viii) communities should maintain a participatory role along the whole process, and it is them that should define the necessity or not of realising such projects.
8. It is vital for any effort to take into account the idiosyncrasy of the country and more importantly the community, where implementing the scheme.
9. A non-profit approach decreases the amount of funds that would need to be channelled to the projects and it is closer to the ideal of creating sustainable projects for social and environmental considerations. On the other hand, a profit-oriented approach could yield better operational results and spread more rapidly the diffusion of renewables in off-grid areas, but would require a larger amount of funds to be channelled. In any case the alternative mechanism appears as an opportunity to finance electricity produced that ensures the long-term operability of projects and quality of the service, hence a more effective channelling of funds with regards of $/kWh produced.
10. The proposed scheme can be easily adapted to other renewable technologies, with the necessary research and evaluation of the values that would be convenient for each one specifically (e.g. biomass, wind, and mini-hydro).
11. The proposed scheme can be useful for countries with the presence of stakeholders (e.g. CONELEC, ESCOs, and municipalities) with similar roles as in Ecuador. The RPT would have

to be adapted to the specific characteristics of each country and to the focus that is desired.

12. Structure of the RPT, business models, financing institutions, coverage of RPT and comparison to other mechanisms can be taken as similar concepts that are applicable to other RET projects and also for other countries. Other countries in Latin America are also seeking to further introduce PV into their off-grid areas (Brazilian Amazons, Chile, Argentina, Peru) where there is the opportunity to introduce a vaster amount of systems. The evaluation and inclusion of the RPT scheme can be a promising approach for these regions as well.

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