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Economic assessment of large power photovoltaic irrigation systems in the ECOWAS region

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ABSTRACT

This paper presents an economic assessment of large power (from tens to hundreds kWp) PV irrigation systems in the ECOWAS region, evaluating the economic feasibility of substituting diesel-powered and grid-powered systems with PV ones. Seven countries from the ECOWAS region were considered and two irrigation operating modes were compared (pumping to a water tank or at constant pressure). Net Present Cost (NPC) values are in the $0.33–41.5 \times 10^5$ \$ range, Internal Rate of Return (IRR) values are in the 8–47% range and Payback Period (PBP) values are in the 2.1–10 years range. The economic savings in terms of Levelized Cost of Energy, LCOE, were also evaluated. LCOE for PV irrigation systems are in the 4.5–17.4 \$cents/kWh range, which represent percentage savings of 30–84% if compared to diesel-powered and grid-powered systems.

1. Introduction

Irrigation for agricultural applications is a very high water and electricity-consuming activity, as most of the water demanded must be pumped from underground reservoirs. Traditionally, water pumps are powered by the local electric grid, if accessible, or by diesel generators in isolated regions or in regions where the grid service is unreliable. In any case, diesel or electricity consumption represents a significant share of the economic cost required in any agricultural plantation. Solar photovoltaic (PV) generators to feed irrigation systems represent an attractive alternative for reducing the cost of this electricity consumption: they can be site-scaled, they permit stand-alone operation and they have a low environmental footprint. Also, they are economically competitive since the prices of PV panels started dropping in 2010 and were reduced to less than half in only 5 years [1].

Up-to-date reviews of the state of the art ([2], [3]), as well as recent international reports ([4], [5]) show that many studies have already evaluated the technical and economic viability of PV water pumping, for both drinking and irrigation applications. However, they all refer to systems with relatively small PV nominal power (up to 30 kW), that present lower efficiencies and higher unit-cost than larger power systems. The aim of this work is to explore the feasibility of PV irrigation systems with enough power to supply water to professional agricultural exploitations (big farmers, irrigator communities and agro-industries) in the range of tens or hundreds of kW.

Recently, the European MASLOWATEN project [6] has reported solutions that solve the technical problems associated to large power PV irrigation systems (like the effect of PV power intermittences, the integration in the previous existing irrigation network or the match between PV production and irrigation needs), evaluating them in 5 real-scale PV irrigation demonstrators installed in Spain, Portugal, Italy and Morocco, ranging from 40 to 360 kWp. The economic effectiveness of these large power systems has been evaluated, obtaining very encouraging results: the Payback Periods (PBP) for substituting the grid-connection or diesel generators in the range of 7–10 years, with Internal Rates of Return (IRR) in the range of 10–16%. However, diesel prices, electricity tariffs, access to the grid and grid resiliency differ from the South of Europe to other regions of the planet, so these results are highly site-dependent. Therefore, it would be interesting to evaluate the economic feasibility of large power irrigation systems in other regions. One of particular interest is the ECOWAS (Economic Community of West African States) region [7], where institutions like the ECREEE (ECOWAS Centre for Renewable Energy and Energy Efficiency) or the World Bank are promoting renewable alternatives

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for agricultural applications [8]. ECOWAS countries are generally characterized by highly decentralized farms, with very limited or unreliable grid-access points. This has favored an abundance of diesel generators for back-up services, with the consequent elevated fuel and transportation costs.

The objective of this paper is to analyze the conditions in which the promising large power PV irrigation systems in stand-alone operation are economically feasible in the ECOWAS region. The analysis starts out with the experimental data from the MASLOWATEN demonstrators, for example, the actual CAPEX depending on their size (from 1.4 to 1.7 €/Wp), and focuses on the substitution of existing diesel or grid-powered systems with PV ones. Following the recommendation of other authors [9], the performance factors used in this economic evaluation are the PBP, the IRR, the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE), which have been calculated for 7 countries from the ECOWAS region. Four different cases were compared for these 7 countries: irrigation pumps could be originally powered with diesel generators or by the national grid (and both would be substituted by a PV generator), and they have two possible operating modes (pumping to a tank or at constant pressure).

This analysis can be useful for other regions and opens the door to rationalize future PV irrigation programs that could be boosted in these areas.

2. Methodology

The purpose of this paper is to evaluate the economic viability of large power PV irrigation systems in the ECOWAS region. Firstly, 7 PV irrigation systems were simulated in stand-alone operation for 7 countries, assuming they would be located in areas with high solar radiation and irrigation needs. It should be noted that these areas are intended to be generic examples of suitable locations, so factors like limited access to water have not been considered for reasons of simplicity. In the same way, only PV irrigation systems without batteries and without any other power sources are considered, therefore they are suitable for farms able to irrigate during the day. The objective of these simulations is to determine the water volume pumped by a given irrigation system, powered by a 380 kWp PV generator, and how much PV energy (PVE) this system would produce over a whole year. Secondly, the viability of the economic investment required for substituting diesel generators or grid-connection points with a PV generator was evaluated through three indicators (NPC, IRR and PBP). Thirdly, the LCOE of the PV-powered systems was estimated and compared with the LCOE of diesel-powered systems and with the national electricity tariffs. Therefore, 4 case studies were considered, depending on whether the irrigation pumps were previously powered with diesel generators or by the national grid, and whether they operate by pumping to a water tank or at constant pressure. In addition, a sensitivity analysis was carried out to assess the effect on the profitability of local electricity tariffs, diesel prices and the size of the PV irrigation system.

2.1. PV irrigation systems simulations

The performance of PV irrigation systems has been simulated using a simulation tool called SISIFO [10]. There are further simulators and toolboxes available for PV irrigation systems [11] [12], but SISIFO links its results to just those inputs guaranteed by the different component manufacturers. This way, responsibilities can be assigned in case of underperformance, favouring the bankability of possible projects. Simulations were carried out for the 7 locations presented in Table 1. Based on it, SISIFO is able to import the monthly mean values of horizontal daily irradiation, as well as the maximum and minimum ambient temperatures for each place from the PVGIS database [13].

Table 1
Location input used for the simulation of the PV irrigation systems.

Country	Region	Latitude [°]	Longitude [°]
Benin	Parc National du W	12.050	3.032
Burkina Faso	Sahel Reserve	14.881	−0.1
Cape Verde	Praia	14.924	−23.533
Guinea	Dinguiraye	11.222	−10.723
Liberia	Voinjama	8.413	−9.748
Nigeria	Kano	12.018	−8.613
Sierra Leone	Fintonia	9.649	−12.225

Table 2
Parameters of the PV module.

Parameter	Value
Cell material	Crystalline silicon
Nominal power of each PV module [Wp]	250
Power model	Only temperature effect
Coefficient of variation of power with temperature - γ [%/°C]	−0.420
Nominal operating cell temperature – NOCT [°C]	45

Table 3
Parameters of the North-South horizontal axis tracker.

Parameter	Value
Separation between trackers in E-W direction	3
Maximum rotation angle [°]	45
Axis orientation [°]	0
Axis inclination [°]	0
Separation between tracker rows in N-S direction	1
Module inclination [°]	0
Backtracking option	Yes

Then, the mean-sky model is used to split the monthly mean daily horizontal global irradiation in its beam and diffuse components, which are calculated using the global diffuse correlations of Erbs [14]. The estimation of the instantaneous values of these components is made as described by Collares-Pereira and Rabl [15]. The Perez model [16] is used for transposition from horizontal to in-plane diffuse irradiances. The Martinez shading model [17] is also used in this simulation. As regards ambient temperatures, the simulation tool is able to generate the time series using a cosine type interpolation model.

The next step is related to the inputs of the electrical characteristics of the PV modules (Table 2) and PV generator structure (Table 3). The 380 kWp PV generator is mounted on a North-South horizontal axis tracker due to its better match between incident irradiance and irrigation needs. It should be highlighted that tracking systems are not usually considered for smaller irrigation systems, as they increase the initial investment and maintenance costs. However, in large power systems the energy gain and the constant daily power profile (which matches the dynamics of the well) obtained using a tracker are important enough to justify a bigger economic effort. Wiring losses in the DC part of the system are 1.5% and in the AC part are 3% (Table 4).

Table 4
Wiring parameters.

Parameter	Value
DC losses [%]	1.5
AC losses [%]	3

Table 5
PV generator size, inverter and pumping characteristics.

Parameter	Water pool	Constant pressure
	Value	Value
PV generator size [kWp]	380	380
Nominal power of the frequency converter [kW]	220	220
Type of PV irrigation system	Stand-alone	Stand-alone
Type of pumping	Water pool	Constant pressure
Static head [m]	200	170
Friction losses at rated flow [m]	20	20
Working pressure [m]	Variable	30
Working flow [m^3/h]	Variable	200

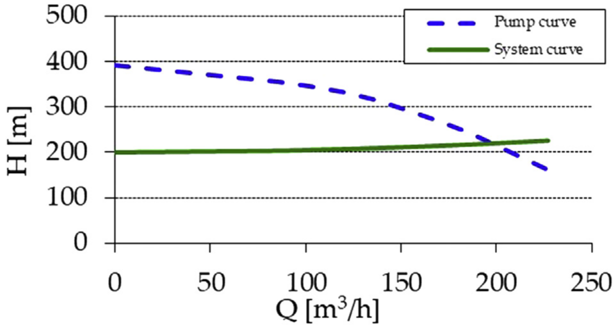


Fig. 1. Pump and system curves.

Table 6
Characteristics of the motor.

Parameter	Value
Nominal power [kW]	165
Nominal RPM	2933.8
Minimum RPM [% of nominal]	60
Maximum RPM [% of nominal]	110
Nominal frequency [Hz]	50

According to the characteristics of the previously defined irrigation systems (one pumping to a water tank and the other at a constant working pressure), the Caprari E10S50/11B MAC10220-8V is used, as well as a 220 kW OMRON frequency converter. Table 5 summarizes the main characteristic of the systems.

Fig. 1 includes the characteristic curves of the pump (at 50 Hz) and the hydraulic system and Table 6 summarizes the characteristics of the motor.

Advanced options influencing the simulation of the system are included in Table 7. Finally, it should be mentioned that all days of the year are simulated, with hourly resolution and using solar time.

2.2. Economic viability analysis

For estimating the values of NPC, IRR and PBP for a monetary investment, the annual Cash Flows (CF) need to be calculated for the whole lifetime of system (25 years), considering both the annual Profits (P) obtained and the Amortization (AM) of the Initial Investment Cost (IIC). In the particular case assessed in this paper, the annual profits are given by the economic savings derived from substituting the national grid (no electricity tariffs would have to be paid) or diesel generators (no diesel fuel would need to be bought) with a PV generator. Entries from selling the crops obtained with the water pumped are not significant in this analysis, as they are the same independently of how the system is powered. In other words, the viability of the PV system is evaluated in terms of the variation in the CF before and after the installation of the PV generator. CF for the year n, for a grid-powered ($CF_{g,n}$) and for a diesel-powered ($CF_{d,n}$) system are given by equations (1) and (2):

Table 7
Advanced simulation options.

Parameter	Value
Soiling [%]	2
Spectral response	Yes
Diffuse model	Perez
Monthly diffuse correlation	Erbs
Shading model	Martinez
Minimum irradiance [W/m^2]	10
Ground reflectance []	0.2

$$CF_{g,\,n} = (E - EC_n) \times (1 - t) \tag{1}$$

$$CF_{d,\,n} = (E - DC_n) \times (1 - t) \tag{2}$$

where E is the entry obtained from selling the crops, EC_n is the cost of the electricity consumed by the grid-powered irrigation system, DC_n is the cost of the diesel consumed by the diesel-powered system and t is the corporate tax rate for a given country.

EC and DC for the year n are given by equations (3) and (4):

$$EC_n = EP \times PVE_n \tag{3}$$

$$DC_n = DP \times PVE_n \times dfc \tag{4}$$

where EP is the electricity price given by the national electricity tariffs, DP is the diesel price per volume unit, $\mathrm{PVE_n}$ is the annual energy generation (assuming that PV modules experience no degradation in the first 5 years of their lifetime and a constant annual degradation of 0.8% after that [18]) and dfc is the average diesel fuel consumption per energy unit, which has been given a value of 0.286 l/kWh according to experimental data [6].

CF for the year n, for a PV-powered system (CF_{pv}) is given by equation (5):

$$CF_{pv,\,n} = \begin{cases} -IIC & (if\ n = 0) \\ (E - OM - RC - AM) \times (1 - t) + AM & (if\ n \neq 0) \end{cases} \tag{5}$$

where OM is the annual Operation and Maintenance Cost and RC is the annual Replacement Cost of the PV system, including the irrigation pumps. These two annual costs, together with the ICC, determine the Life Cycle Cost (LCC) of a PV system [19].

The variation in CF for the year n when substituting a grid-powered ($\Delta CF_{g,n}$) or a diesel-powered system ($\Delta CF_{d,n}$) with a PV powered one is given by equations (6) and (7):

$$\Delta CF_{g,\,n} = \begin{cases} -IIC & (if\ n = 0) \\ CF_{pv,\,n} - CF_{g,\,n} = (EC_n - OM - RC) \times (1 - t) + AM \times t & (if\ n \neq 0) \end{cases} \tag{6}$$

$$\Delta CF_{d,\,n} = \begin{cases} -IIC & (if\ n = 0) \\ CF_{pv,\,n} - CF_{d,\,n} = (DC_n - OM - RC) \times (1 - t) + AM \times t & (if\ n \neq 0) \end{cases} \tag{7}$$

OM and RC were estimated as 2% of the IIC each [20] and AM was calculated assuming a constant amortization linear coefficient of 7% of the IIC [21]. The IIC of the PV irrigation system was estimated at a unit cost of 1.7 $/Wp [6] –consistent with the values obtained in previous studies [22]-, assuming a 20% cost overrun in the ECOWAS region compared to the South of Europe (where the CAPEX is 1.4 $/Wp), due to the decentralized character of farms in the region.

Once $\Delta CF_{g,n}$ and $\Delta CF_{d,n}$ are calculated for the lifetime of system (25 years), the NPC can be estimated according to equations (8) and (9):

$$NPC_g = \Delta CF_{g,\,0} + \sum_{n=1}^{25} \frac{\Delta CF_{g,\,n}}{(1+i)^n} \tag{8}$$

$$NPC_d = \Delta CF_{d,\,0} + \sum_{n=1}^{25} \frac{\Delta CF_{d,\,n}}{(1+i)^n} \tag{9}$$

where i is the real interest rate for a certain country, given by equation (10) [23], [24]:

$$i = \frac{(i' - f)}{(1+f)} \tag{10}$$

where i' is the nominal interest rate and f is the annual GDP deflator rate (which applies to all the economic activities in a country, including final goods and services). When equation (10) gives a negative value for i (which means that it is necessary to pay an interest rate for investing in a national bank, instead of making a profit), the NPC calculations are made with $i = 0$ [24].

Finally, the IRR is defined as the real interest rate that would make NPC = 0 after 25 years (i.e. the real interest rate at which the initial investment is returned at the end of the lifetime of the project [9]), and PBP is defined as the number of years (n) for which $\sum_{n=0}^{25} \Delta CF_{g,\,n} = 0$ (i.e. the period of time required for the initial investment to be returned with the present value of cash flows, disregarding the real interest rate [9]).

Some input variables used in this economic model are country-dependent. Table 8 shows the values assigned to these input variables for the 7 selected countries, together with the corresponding references from which they were obtained.

2.3. Levelized Cost of Energy (LCOE)

LCOE is defined as the lifetime cost of a certain energy generation system divided by the total energy production during this lifetime. It is given by equation (11) [30], [31]:

$$LCOE = \frac{\sum_{n=0}^{25} \frac{(IIC+OM+FC_n)}{(1+i)^n}}{\sum_{n=0}^{25} \frac{PVE_n}{(1+i)^n}} \tag{11}$$

where FC_n is the Fuel Cost necessary to operate the system for the year n. For PV-powered irrigation systems, FC_n is zero and OM is estimated as 2% of the IIC [20]; for diesel powered systems, IIC is zero, OM is assumed to be 40$/kW per year [32] and FC_n is equal to DC_n; for grid-powered systems, LCOE is equivalent to the electricity tariff.

3. Results

3.1. PV irrigation systems simulations

Table 9 summarizes the yearly mean of the daily water volume

Table 8
Input values assigned to country-dependent variables for the 7 selected countries.

Country	EP ($/kWh) [25]	DP ($/l) [26]	t (%) [27]	i' (%) [28]	f (%) [29]	i (%) [23], [24]
Benin	0.23	0.82	9.96	5.6	−0.2	5.8
Burkina Faso	0.25	0.94	16.24	5.6	2.9	2.6
Cape Verde	0.33	0.97	18.26	9.6	−0.9	10.6
Guinea	0.16	0.89	0	4.8	10.6	0
Liberia	0.56	0.83	35.35	13.6	5	8.2
Nigeria	0.20	0.55	17.46	16.9	9.6	6.7
Sierra Leone	0.26	0.78	17.27	18	4.2	13.24

Table 9
Yearly mean of the daily water volume pumped (m^3/day), DC energy consumed (MWh) and the equivalent volume of diesel consumed ($x10^3$ l) by the simulated irrigation systems over a whole year of operation, for the 7 countries under study.

Country	To a water tank			At constant pressure		
	Water (m^3/day)	E_{DC} (MWh)	Diesel ($x10^3$l)	Water (m^3/day)	E_{DC} (MWh)	Diesel ($x10^3$l)
Benin	2343	913.9	261.1	1769	606.6	173.3
Burkina Faso	2361	949.1	271.2	1832	628.6	179.6
Cape Verde	2321	932.5	266.4	1800	617.1	176.3
Guinea	2346	918.4	262.4	1800	617.5	176.4
Liberia	2283	851.8	243.4	1667	571.6	163.3
Nigeria	2344	916.8	261.9	1783	611.7	174.7
Sierra Leone	2299	866.9	247.7	1769	606.6	173.3

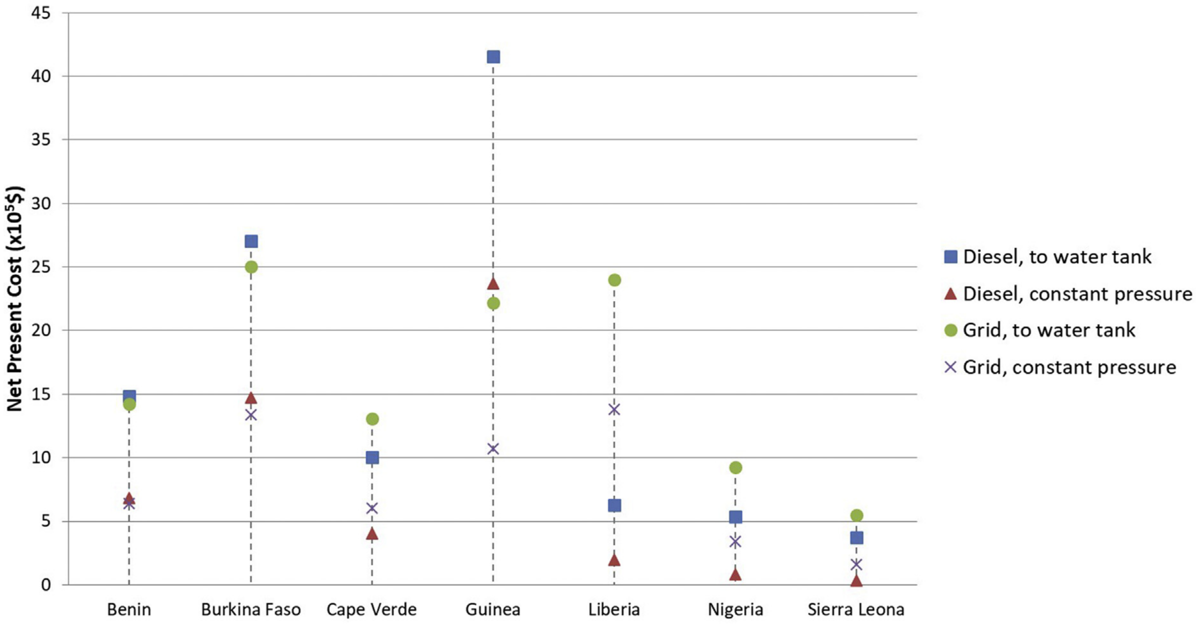


Fig. 2. NPC (x10^5\$) for the 7 countries and the 4 cases under study: substitution of diesel generators or the grid with PV irrigation systems, for both operating modes (to a water tank or at constant pressure).

pumped and the energy consumed - in terms of DC electricity and volume of diesel-by the simulated systems, for the 7 given countries. It is observed that the water volume pumped is always higher when the system is pumping to a water tank than at constant pressure. This difference appears because in the first case the operation point is not constant, since the frequency of the pump varies with the instantaneous available PV power. On the other hand, pumping at constant pressure means working in a specific point of the pump curve, with both constant pressure and flow and, as a consequence, constant power. In other words, when pumping to a water tank it is possible to operate at the PV Maximum Power Point (MPP); when pumping at constant pressure, the PV generator generally operates at a lower power point.

3.2. Economic viability analysis

Figs. 2–4 show the values of NPC, IRR (together with the real discount rate in each country for their comparison) and PBP obtained for the 7 countries and for the 4 cases under study. Substituting an existing grid-powered or diesel-powered irrigation

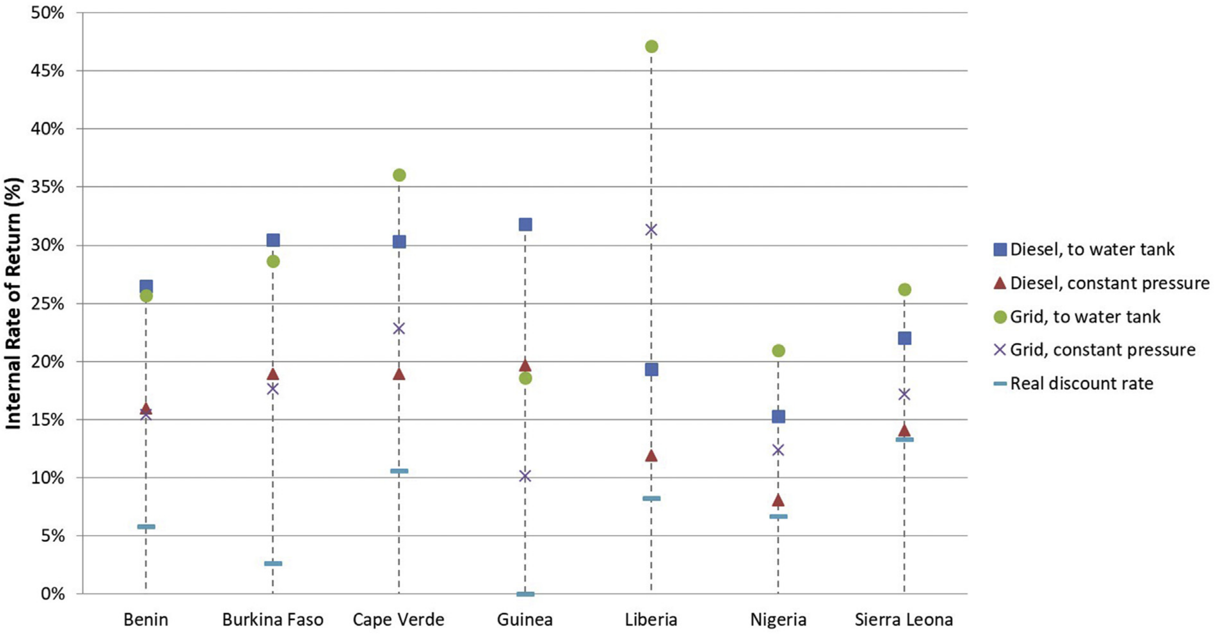


Fig. 3. IRR (%) and local i (%) for the 7 countries and the 4 cases under study: substitution of diesel generators or the grid with PV irrigation systems, for both operating modes (to a water tank or at constant pressure).

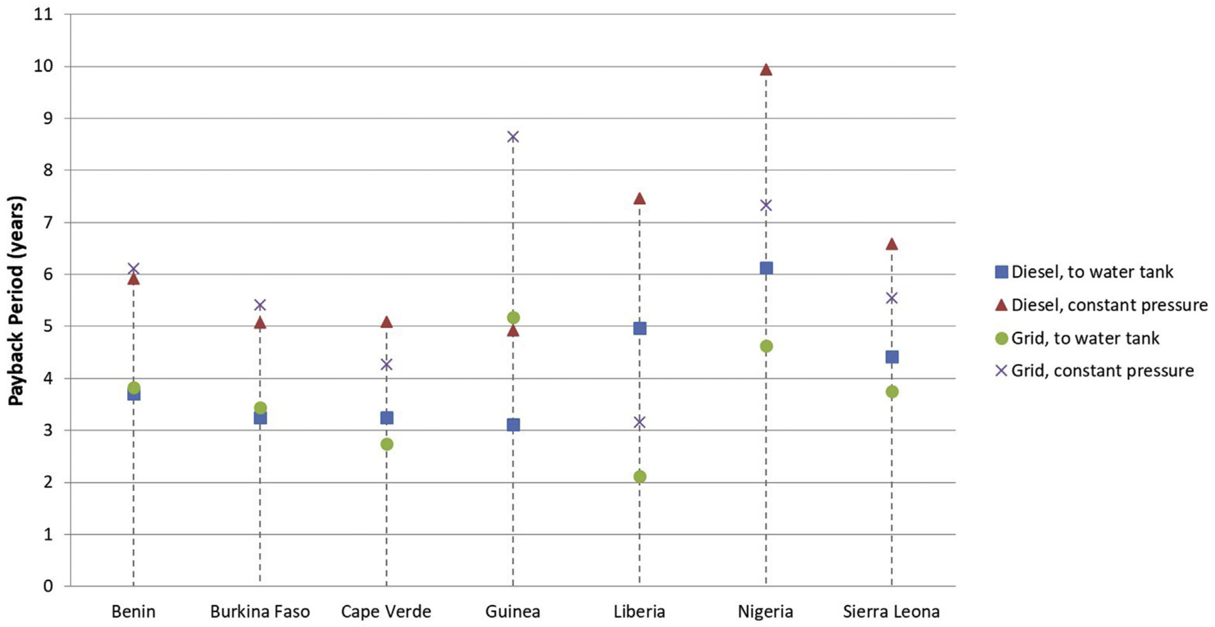


Fig. 4. PBP (years) for the 7 countries and the 4 cases under study: substitution of diesel generators or the grid with PV irrigation systems, for both operating modes (to a water tank or at constant pressure).

Table 10
Electricity prices ($cents/kWh) and LCOE ($cents/kWh) for PV and diesel-powered systems for the 7 countries under study. Values between brackets represent the percentage saving in terms of LCOE for PV irrigation systems compared to grid-powered and diesel-powered systems, respectively.

Country	Electricity price ($cents/kWh)	LCOE ($cents/kWh)			
		Diesel, to water tank	Diesel, constant pressure	PV, to water tank	PV, constant pressure
Benin	22.8	25.2	26.1	7.2 (69) (71)	10.8 (53) (59)
Burkina Faso	25.4	28.6	29.4	5.4 (79) (81)	8.2 (68) (72)
Cape Verde	32.5	29.6	30.3	9.7 (70) (67)	14.6 (55) (52)
Guinea	16.4	27.2	28.1	4.5 (72) (83)	6.7 (59) (76)
Liberia	55.6	25.6	26.5	9.1 (84) (64)	13.6 (76) (49)
Nigeria	20.2	17.5	18.3	7.6 (62) (56)	11.4 (44) (38)
Sierra Leone	25.9	24.1	24.9	12.2 (53) (50)	17.4 (33) (30)

system with a PV-powered system would be cost effective when NPC is positive, IRR is higher than the local discount rate [33] and PBP is significantly lower than the lifetime of system (25 years). It can be observed that these conditions are met for all the cases under study.

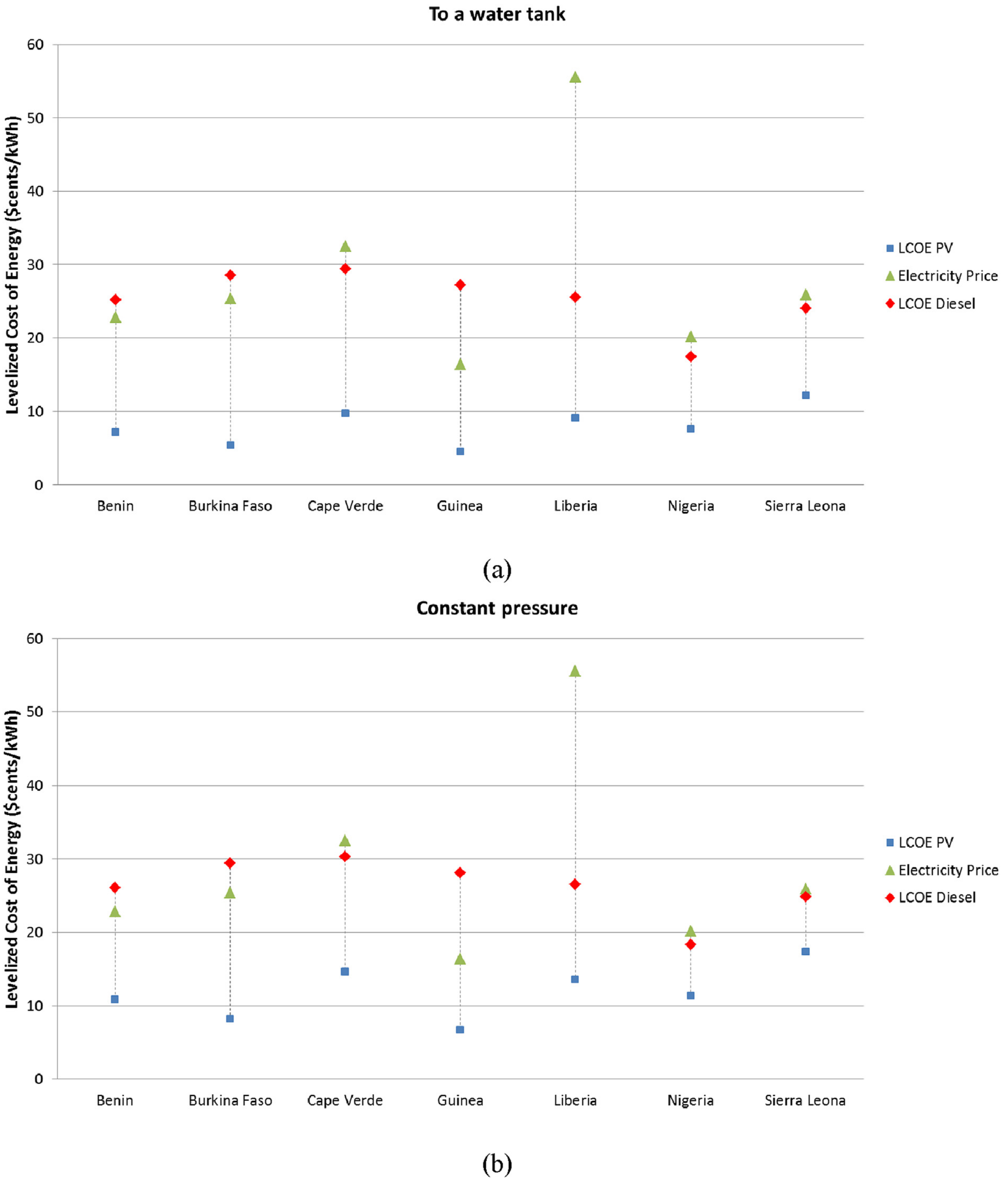
If comparing the 7 countries in terms of NPC, Guinea offers the best profitability for the substitution of diesel-powered systems because of its elevated diesel price and its low real discount rate and corporate tax rate (both equal to zero); Burkina Faso presents the highest profitability for the substitution of grid-powered systems due to its low real interest rate, although it has an intermediate electricity price. In terms of IRR, Guinea also offers the best profitability for the substitution of diesel-powered systems because fuel is very expensive in this country, which implies big savings for a PV powered system, and the income tax rate is zero; Liberia offers the highest IRR for the substitution of a grid-powered system due to the elevated electricity prices, despite it having the highest income tax rate.

If comparing the 4 cases under study, the substitution of diesel-powered systems pumping to a water tank are the most cost effective in Benin, Burkina Faso and Guinea, while the substitution of grid-powered systems pumping to a water tank are the most cost effective in Cape Verde, Liberia, Nigeria and Sierra Leone. In general terms, PV irrigation systems working at constant pressure have lower profitabilities because they are able to pump a smaller volume of water with the same PV generator capacity, which implies a lower economic entry for the same IIC.

As regards PBP values, they are less than 10 years for all the cases under study, and lower than 6 years (which represents less than a quarter of the lifetime of the system) except for some systems pumping at constant pressure.

3.3. *Levelized Cost of Energy (LCOE)*

Table 10 and Fig. 5 show the values of LCOE obtained for diesel-powered and PV-powered systems pumping to a water tank (a) and at constant pressure (b), together with electricity prices for the 7 countries under study. Values between brackets in Table 10 represent the percentage saving in terms of LCOE for PV irrigation systems compared to grid-powered and diesel-powered systems, respectively. Generally, LCOE are smaller for systems pumping to a water tank than at constant pressure, as they are able to pump more water with the same power capacity. It is important to highlight that generating electricity for irrigation applications would be cheaper by far with a PV generator than with the electric grid or with diesel generators: percentage savings are all higher than 30%, the majority of them higher than 50%.



(a)

(b)

Fig. 5. LCOE ($cents/kWh) for PV-powered and for diesel-powered systems and electricity prices for the 7 countries under study, for systems pumping to a water tank (a) or at constant pressure (b).

3.4. Sensitivity analysis

3.4.1. Electricity tariffs and diesel prices

A sensitivity analysis has been carried out to consider how the variation in electricity tariffs or diesel prices, which have been historically very unstable in the ECOWAS region (especially the diesel prices), may affect the profitability of the PV irrigation system. Diesel prices have varied by ±25% of the base case value with an interval step of 5%; electricity tariffs, which are less likely to experience significant changes in the near future, have varied by ±10% of the base case value, with an interval step of 2%.

Figs. 6–8 detail the variation in NPC, IRR and PBP with DP for systems pumping to a water tank (a) or at constant pressure (b), and their variation with EP for the same two operating modes (c), (d). It can be observed that NPC has a linear correlation with DP and with EP. The slope of the corresponding trend line increases when *i* decreases (Guinea has the biggest slope and Sierra Leone, the

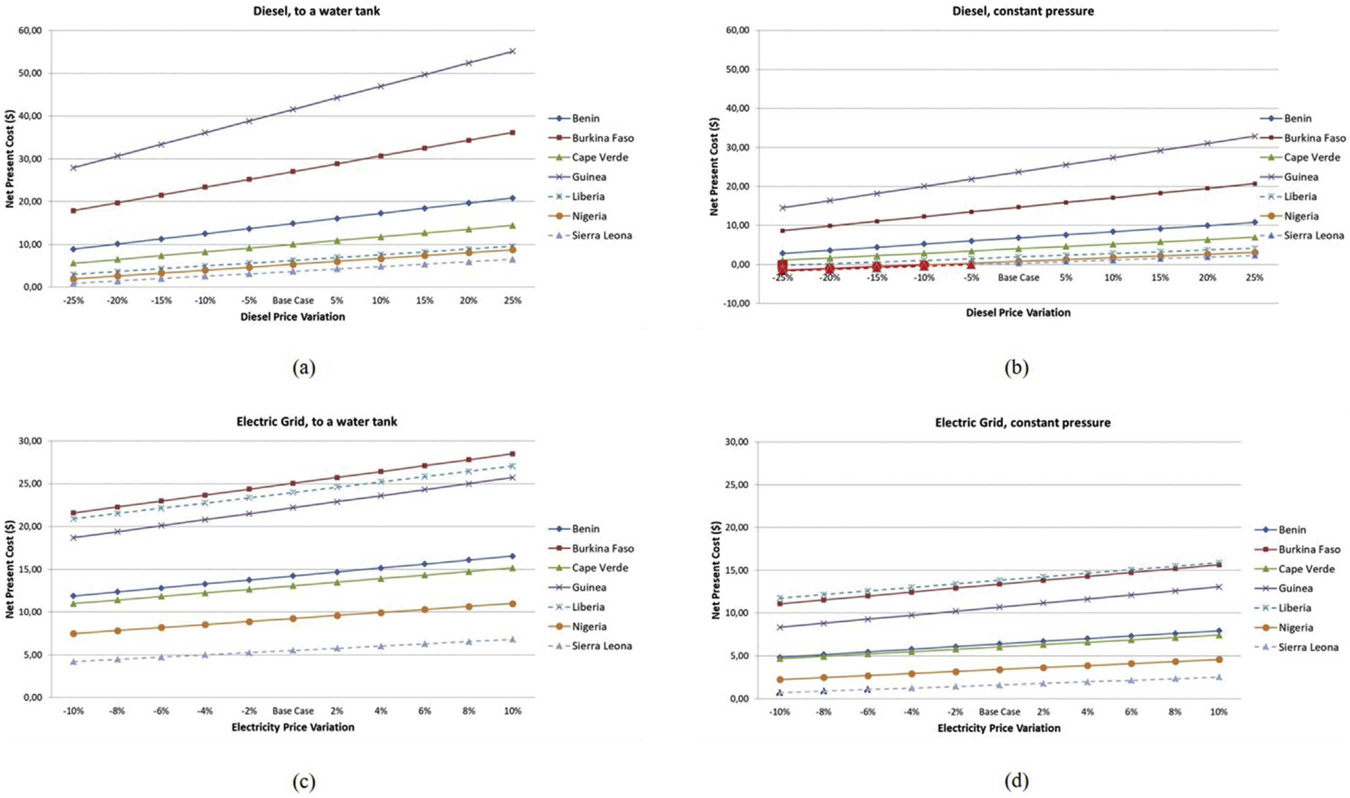


Fig. 6. Variation in NPC ($) with DP for systems pumping to a water tank (a) or at constant pressure (b) and variation in NPC with EP for the same two operating modes (c), (d). Points plotted in bigger markers correspond to negative NPC values.

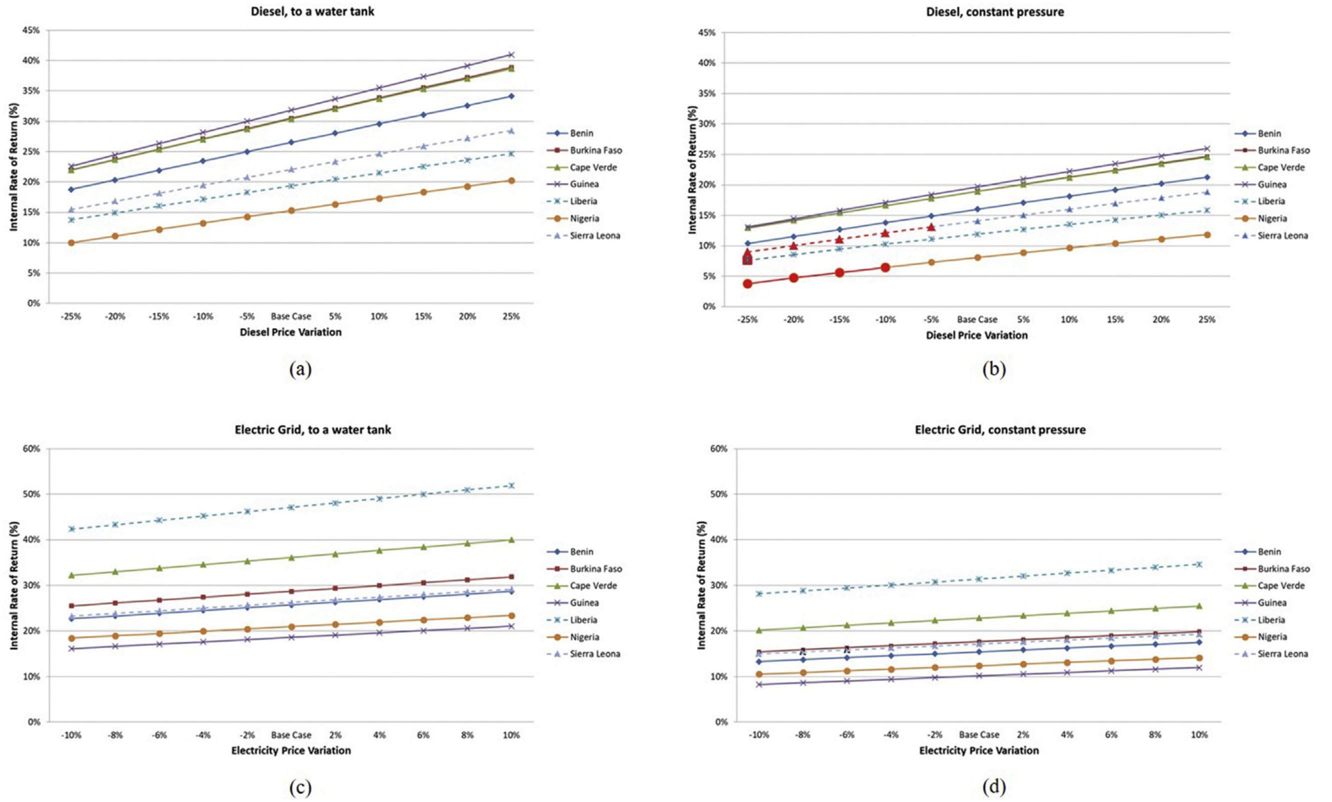


Fig. 7. Variation in IRR (%) with DP for systems pumping to a water tank (a) or at constant pressure (b) and variation in IRR with EP for the same two operating modes (c), (d). Points plotted in bigger markers correspond to IIR values lower than the local *i*.

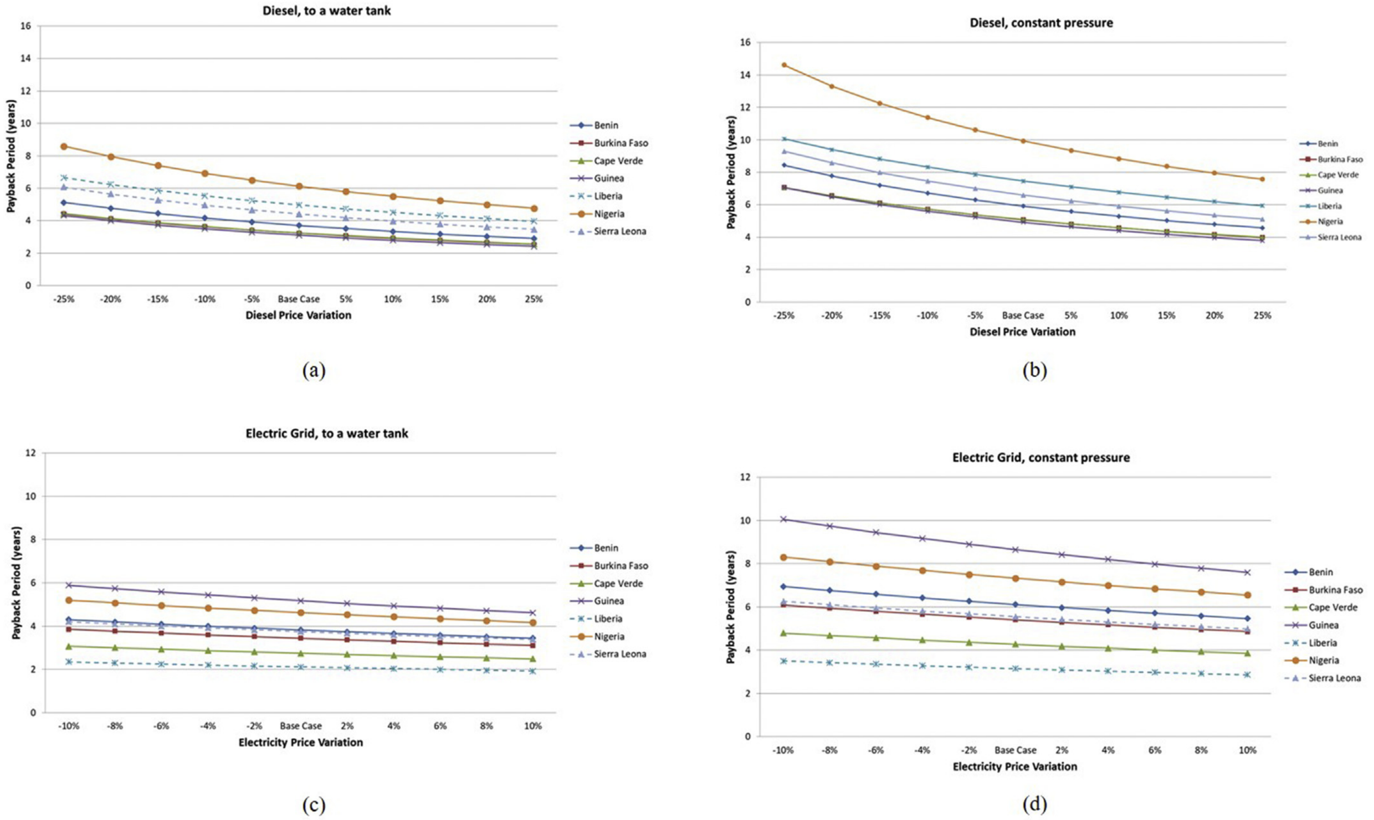


Fig. 8. Variation in PBP (years) with DP for systems pumping to a water tank (a) or at constant pressure (b) and variation in PBP with EP for the same two operating modes (c), (d).

Table 11
NPC values (x10^5\$) obtained for the 380 kWp system (columns shadowed in grey) and for the two smaller irrigation systems considered in the sensitivity analysis.

PV Power (kWp)	Diesel, to water tank			Diesel, constant pressure			Grid, to water tank			Grid, constant pressure		
	45	150	380	45	150	380	45	150	380	45	150	380
Benin	1.5	5.6	14.9	0.7	2.6	6.8	1.4	5.3	14.2	0.6	2.4	6.4
Burkina Faso	2.9	10.4	27.0	1.7	5.8	14.7	2.7	9.6	25.1	1.5	5.2	13.4
Cape Verde	1.0	3.7	10.0	0.3	1.4	4.0	1.3	4.9	13.1	0.6	2.2	6.1
Guinea	4.5	16.0	41.5	2.6	9.2	23.7	2.3	8.3	22.2	1.0	4.0	10.7
Liberia	0.6	2.3	6.3	0	0.5	2.0	2.6	9.2	24	1.4	5.1	13.8
Nigeria	0.4	1.8	5.4	−0.1	0.1	0.8	0.9	3.4	9.3	0.3	1.2	3.4
Sierra Leone	0.2	1.2	3.7	−0.2	−0.3	0.3	0.5	1.9	5.5	−0.1	0.2	1.6

Table 12
IRR values (%) obtained for the 380 kWp system (columns shadowed in grey) and for the two smaller irrigation systems considered in the sensitivity analysis.

PV Power (kWp)	Diesel, to water tank			Diesel, constant pressure			Grid, to water tank			Grid, constant pressure		
	45	150	380	45	150	380	45	150	380	45	150	380
Benin	21	24	27	13	15	16	20	23	26	12	14	15
Burkina Faso	24	28	30	16	18	19	23	26	29	15	17	18
Cape Verde	24	28	30	15	18	19	29	33	36	19	21	23
Guinea	25	29	32	16	18	20	14	17	19	7	9	10
Liberia	15	18	19	8	10	12	39	43	47	25	28	31
Nigeria	12	14	15	6	7	8	16	19	21	10	11	12
Sierra Leone	17	20	22	9	12	14	21	24	26	12	15	17

lowest). As well as NPC, IRR presents a linear correlation with DP and EP, although in this case the slope of the corresponding trend line does not depend on *i*, but on both *t* (higher *t* means smaller slopes) and DP or EP (higher prices mean bigger slopes). Finally, PBP changes with DP and EP according to a negative exponential trend. The exponent coefficient depends on *t* (higher income tax rates mean higher coefficients) and on DP or EP (higher prices mean lower coefficients).

In Fig. 6(b)—diesel-powered systems pumping at constant pressure-, points with negative NPC values (which imply that the investment of installing a PV irrigation system would not be cost effective) are plotted in bigger markers. As observed, NPC would be

Table 13
PBP values (years) obtained for the 380 kWp system (columns shadowed in grey) and for the two smaller irrigation systems considered in the sensitivity analysis.

PV Power (kWp)	Diesel, to water tank			Diesel, constant pressure			Grid, to water tank			Grid, constant pressure		
	45	150	380	45	150	380	45	150	380	45	150	380
Benin	4.6	4.1	3.7	7.1	6.3	5.9	4.8	4.2	3.8	7.3	6.5	6.1
Burkina Faso	4.0	3.5	3.2	5.9	5.4	5.1	4.3	3.8	3.4	6.3	5.7	5.4
Cape Verde	4.0	3.6	3.3	6.1	5.5	5.1	3.4	3.0	2.8	5.1	4.6	4.3
Guinea	3.9	3.4	3.1	6.0	5.3	4.9	6.6	5.7	5.2	11.0	9.4	8.7
Liberia	6.1	5.4	5.0	9.4	8.3	7.5	2.6	2.3	2.1	4.0	3.5	3.2
Nigeria	7.8	6.7	6.1	12.0	10.7	9.9	5.8	5.1	4.6	8.8	7.9	7.3
Sierra Leone	5.5	4.8	4.4	9.1	7.6	6.6	4.7	4.1	3.8	7.6	6.4	5.6

negative in Sierra Leone if DP fell below 5% of the base case value, in Nigeria if DP fell below −10% and in Liberia if DP fell below −25%. In Fig. 7(b), points with IRR values lower than the real discount rate are also plotted in bigger markers, and they correspond to the same cases that present negative NPC values. For grid-powered systems, NPC is positive and IRR is higher than real discount rates for all the situations considered in this sensitivity analysis. On the other hand, all PBP's obtained are lower by far than the lifetime of system (25 years), with a maximum value of 14.6 years in the worst case scenario for Nigeria (see Fig. 8b), but with maximum values of 10 years for the rest of the countries.

3.4.2. System size

An additional sensitivity analysis has been carried out to consider how the profitability of the system might change with the system size, which mainly affects its pumping efficiency (the larger the PV generator, the higher the pumping efficiency) and its unit costs (the larger the system, the smaller unit costs). Two additional PV irrigation systems have been considered (150 and 45 kWp), both in the range of what we are here calling “large power”. Unit costs of 1.84 and 2.05 $/Wp have been considered, based on the MASLOWATEN experience with two demonstrators equivalent in size terms [4]. As well as for the base case, a 20% cost overrun has been assumed in the ECOWAS region compared to the South of Europe.

Tables 11–13 show NPC, IRR and PBP values obtained for the 380 KWp system (columns shadowed in grey) and for the two smaller systems considered in this sensitivity analysis. In general terms, smaller systems are less profitable than larger ones, but not significantly. Highlighted values in Tables 11 and 12 correspond to those cases where PV irrigation systems would not be profitable (negative NPC or IRR smaller than the local real discount rate), all of them corresponding to systems pumping at constant pressure. However, it should be noted that such cases are not cost-efficient by a very small margin, so this could be easily improved with slight design modifications to reduce the investment cost.

4. Discussion

The first point of discussion on the previous results is that the installation of stand-alone large power PV generators in the ECOWAS region would be very profitable in already existing grid-powered and diesel-powered irrigation systems. The results of this work state that PV irrigation systems are not only advantageous when there is no access to the grid or in regions with unreliable grid service (where diesel generators are used as back-up) as Chandel et al. have noted [34]; but also they are actually more cost-effective than the electric grid itself. So, PV irrigation should be implemented even in regions with good grid access.

The second aspect to discuss is the advantages of PV irrigation systems with accumulation in terms of water tanks. Section 3.1. shows that they are more profitable than systems pumping at constant pressure, although this might change if the use of low-pressure sprinklers was considered for the second. Furthermore, pumping to a water tank offers a significant advantage: water can be stored in the tank for its later use when solar radiation it too low, while constant-pressure systems need to couple irrigation periods to PV generation (which implies that irrigation is not possible during the night). The use of batteries would be a possible solution for constant-pressure systems, but is has not been considered in this study as they still present some technical and economic challenges, as Campana et al. have shown [35].

Third, the sensitivity analysis carried out in section 3.4.1 shows that the profitability of large power PV irrigation systems is reasonably independent of possible changes in electricity tariffs or diesel prices. Only diesel-powered systems pumping at constant pressure are likely to become unprofitable in Liberia, Nigeria and Sierra Leone. Nevertheless, diesel prices would need to be reduced by more than 10%, which is not likely to happen in the near future. This means that the investment in PV irrigation systems is protected against these price variations, reducing its risk. As for the sensitivity analysis detailed in section 3.4.2, it can be extracted that the profitability of PV irrigation systems improves for larger systems, and therefore the investment is even more protected against these price changes.

Fourth, it is important to highlight the small PBP values obtained in this work for the four cases under study, which are all lower than half the lifetime of the system. In fact, most cases (except some systems pumping at constant pressure) present PBP values of less than 6 years, which is less than a quarter of the lifetime of the system. These results are aligned with or improve those presented by other authors like Campana et al. [20], Chandel et al. [34] and Li et al. [2]. This implies again a significant reduction in the investment risk associated to the installation of the PV system: the faster the initial investment cost is returned, the less the probability of unforeseen events happening. As for the sensitivity analysis, with the exception of Nigeria with a 25% reduction in diesel prices for a system pumping at constant pressure, the rest of the countries present a PBP of less than 10 years, which is very competitive and softens the possible risks.

The fifth aspect to discuss is that financing entities have traditionally evaluated the bankability of PV projects by referring to the Performance Ratio (PR) of the system over a whole year of operation. This PR represents the ratio between the PV energy that has actually been generated and the energy that could have ideally been generated for a given yearly irradiation. Results from section 3 have been obtained considering that the PV energy generated is the one resulting from the simulation described in section 2.1, but this generation, and therefore the PR value, is highly affected by factors that do not depend on the PV system quality: seasonal water availability, water usage or the water needs of different crops. This must be taken into account when presenting performance evaluations of this type of system, especially if comparing them to other PV applications. This aspect is very relevant and deserves further research.

Finally, the installation of large power PV irrigation systems demands significant monetary efforts [3] [36], [37], which need to be justified with very detailed business plans based on an economic analysis like the one presented here. Such business plans assume that systems operate both correctly and efficiently during their entire lifetime, and this requires the following [37]: the design of a control logic capable of managing power intermittences due to cloud-passing (that can induce over-voltages in the electric system or water hammers in the hydraulic system, reducing the overall lifetime), the complete integration of the PV system into the pre-existing irrigation infrastructure, the use of solar trackers (for matching PV generation and irrigation needs) and the drawing up of technical specifications and quality control procedures to assure the long-term reliability. The future PV irrigation programs should include a comprehensive economic analysis like the one developed in this work and give the greatest importance to these aspects. Solutions to them have been given by the aforementioned initiatives, but they should be adapted to the specific characteristics of each region.

5. Conclusions

This paper presents an economic assessment of large power (in the range from tens to hundreds of kWp) PV irrigation systems in the ECOWAS region, considering the investment required for their installation. The profitability of this investment was evaluated through three indicators (NPC, IRR and PBP) for 7 different countries and 4 case studies: substitution of diesel generators or the grid with PV irrigation systems, for two operating modes (pumping to a water tank or at constant pressure). Additionally, the LCOE values of a diesel-powered, a grid-powered and a PV irrigation system were estimated for their comparison. Finally, a sensitivity analysis was carried out to evaluate how the three economic indicators can vary with diesel prices (DP), electricity prices (EP) and the size of the system. The following conclusions could be drawn:

- NPC values are all positive and in the range $0.33–41.5 \times 10^5$ \$. NPC present a linear correlation with DP and EP.
- IRR values are all higher than the local real discount rate (*i*) and in the 8–47% range. IRR presents a linear correlation with DP and EP.
- PBP are far below the lifetime of system (25 years) and in the 2.1–10 years range. PBP presents an exponential correlation with DP and EP.
- LCOE values are the lowest for PV irrigation systems and in the 4.5–17.4 $cents/kWh range, representing very high percentage savings in the range 30–84% if compared to diesel-powered and grid-powered systems.

In general terms, substituting diesel-powered and grid-powered systems with PV irrigation systems in the region of ECOWAS seems very promising from the economic point of view. Profitabilities are higher when the irrigation system is pumping to a water tank than at constant working pressure, and they present little sensitiveness to variations in DP or EP and to the size of the system.

In any case, the study here presented is a starting point and is limited to a region and to certain conditions, but it can be extended in the future by means of more detailed considerations:

- Only locations with very high annual irradiances have been considered, but it would be useful to estimate the profitabilities of PV irrigation systems in regions with fewer solar resources available.
- Only PV configurations in stand-alone operation without batteries have been simulated. However, there are many applications where hybrid configurations, whether with the local grid or with other energy sources, are not only possible but also very beneficial (or even the only solution if irrigation during the night is necessary). The analysis of the feasibility of these solutions would be a very interesting future work.
- As mentioned in section 4, the bankability of PV projects is often evaluated through the PR of the system, which in irrigation applications can be affected by external factors. It is recommended that future works include information related to the water availability, water usage and type of crops, in order to perform more accurate and site-specific economic evaluations.

The probable growth in the market of large power PV irrigation systems should be accompanied by an effort in policy aspects related to administrative permissions and ad-hoc financing schemes. These are the main barriers for the market uptake of these systems once their technical and economic viability have been proven.

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