EXPERIENCE WITH PV-DIESEL HYBRID VILLAGE POWER SYSTEMS IN SOUTHERN MOROCCO

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SUMMARY

In October 2002, under the auspices of Spanish Cooperation, a pilot electrification project put into operation two centralised PV-diesel hybrid systems in two different Moroccan villages. These systems currently provide a full-time energy service and supply electricity to more than a hundred of families, six community buildings, street lighting and one running water system. The appearance of the electricity service is very similar to an urban one: one phase AC supply (230V/50Hz) distributed up to each dwelling using a low-voltage mini-grid, which has been designed to be fully compatible with a future arrival of the utility grid. The management of this electricity service is based on a "fee-for-service" scheme agreed between a local NGO, partner of the project, and electricity associations created in each village, which are in charge of, among other tasks, recording the daily energy production of systems and the monthly energy consumption of each house. This register of data allows a systematic evaluation of both the system performance and the energy consumption of users. Now, after four years of operation, this paper presents the experience of this pilot electrification project and draws lessons that can be useful for designing, managing and sizing this type of small village PV-hybrid system.

Keywords: PV-diesel hybrid systems, rural electrification.

1. INTRODUCTION

PV-diesel hybrid systems are nowadays recognised as a promising alternative to isolated diesel generators for rural village electrification purposes. Although case studies found in the literature[1-4] depend on the particular characteristics of each site (remoteness, accessibility, fuel and transport costs, etc.), they all agree that it is technically and economically feasible to replace small diesel generators, up to a few tens of kW, with PV-diesel hybrid systems. Potential advantages are, for example, the reduction of fuel consumption (engines run less time and more efficiently) and lower operation and maintenance costs. Hybrid systems also adapt to the growth in energy consumption (by increasing engine run time) and can provide a highly reliable, full-time AC electricity service (through the existence of redundant generators). For example, the largest village power electrification initiative, the Chinese "Brightness Program", has relied on this technology for electrifying tens of thousands of rural village in Western China. During the last two years, around 800 villages have been electrified with PV and PV-diesel hybrid systems totalling an installed PV capacity[5] of 15·7 MWp.

On a smaller scale, the IES-UPM participated in a pilot electrification project funded by Spanish Cooperation which commissioned, in October 2002, two PV-diesel hybrid systems in the Moroccan villages of Iferd and Idboukhtir, which belong, respectively, to the provinces of Zagora and Ouarzazate, located in the south of the country. The origin of this project was the on-site evaluation of a previous PV pumping program[6], in which we discovered that the region presented suitable characteristics for village electrification. In most of villages visited we found collective property diesel generators which supplied electricity to dwellings from 3 to 4 hours per day. This finding should not attract attention because diesel generators have been the only alternative for decentralised rural electrification for a long time owing to their relatively low investment cost. Nevertheless, the fact that most of these systems operated continuously was certainly a surprise to us. For example, in Iferd there was a diesel generator that has worked since 1990 in spite of the frequent breakdowns, the need for re-investment (five motors and two alternators have been used in twelve years, all of which were second hand), the fuel costs, or the difficulties in transporting it from the nearby diesel station situated 20 km away.

In this context, the idea emerged of replacing some diesel generators with PV-diesel hybrid systems because, on the one hand, populations seemed to have good organisational skills (that were later confirmed) and could take care of the service management as well as the basic operation and maintenance of the systems, which was of particular importance because of the lack of technical infrastructures in the region. And, on the other hand, because the inhabitants were willing to pay for a better energy service, which highlighted the possibility of ensuring the long-term maintenance of systems.

Both villages were a selected by a local NGO, the Tichka Association[7], partner in the Project. The first village, Iferd, had already been beneficiary of the previous PV pumping program[6]. The new hybrid system replaced their old diesel generator, which was incorporated as an energy backup, and supplies electricity to 77 dwellings, three community buildings (mosque, local association and school) as well as street lighting. The second village, Idboukhtir, was not previously electrified, although a few families had installed small solar home systems and were familiar with PV technology. In this village, the hybrid system provides a joint electricity service (to 29 dwellings, three community buildings and street lighting) as well as running water (with taps in each dwelling).

The management of the electricity service is based on a “fee-for-service” scheme agreement, before the systems went into commission, between Tichka and electricity associations created in each village. This agreement included a progressive electricity tariff and some initial precautions for controlling the growth of energy consumption: service limited to 14 hours per day, prohibition of several domestic appliances (refrigerators, electric cookers and heaters, etc.) and the obligatory use of fluorescent lamps. Some of these initial rules were later modified, for example, reducing the tariff, increasing the service up to 24 hours a day, or permitting the use of refrigerators.

Among other obligations, the village electricity associations are responsible for recording the daily energy production of the system and the monthly energy consumption of each house. This way, the system performance and the energy consumption are continuously monitored. These associations are also in charge of invoicing, collecting the corresponding money, and carrying out basic operation and maintenance tasks, such as cleaning the PV generator or refilling the batteries with distilled water.

Now, after four years of operation, this paper presents the experience of this pilot electrification project and draws lessons that can be useful for designing, managing and sizing this type of small village PV-hybrid system.

2. SYSTEM DESIGN

2.1 PV-diesel configuration

Each village system has been installed in a building constructed by the Project's beneficiaries (figure 1-a). The system's components are arranged in the switched topology[8,9] shown in figure 1-b, which is the most common configuration used today in hybrid systems[10] despite its having some slight drawbacks. For example, there is a momentary blackout when the mini-grid supply is switched from inverter to diesel generator and vice versa. The inverter and the diesel generator are also unable to operate in parallel (combining their respective power) and one of them must be sized to handle the peak load demand (this drawback is overcome by parallel inverters[11, 12], but their use is not still widespread in current rural applications).

One-phase AC power has been chosen because three-phase inverters have limited the power per phase to a third of their rated power, which requires a proper balanced load. The latter condition is difficult to ensure in small systems that supply a reduced number of dwellings and potential highly unbalanced loads would cause an inverter shutdown[13]. One disadvantage is that one-phase inverters are unable to operate three-phase motors, although this drawback can be easily solved using standard frequency converters, which are very common in industry and in present PV pumping applications[14-16]. Frequency converters also allow a soft starting of three-phase motors, which avoids undesirable short-term inverter overloads caused by the high starting currents of one-phase ones[17].

Figure 1. (a) Idboukhtir village system. (b) Switched topology.

2.2 Mini-grid topology

The local mini-grid is radial and underground. Usually, despite the elimination of poles, underground cabling is more expensive than overhead and poses more difficulties in case of future repairs (e.g., location and detection of faults) or an increase in load demand, which may require new line extensions, replacement of cables, etc. Nevertheless, for this particular project, underground cabling has been the least costly option because users carried out most of civil work. To give an idea of this effort, figure 2 shows the mini-grid layout in Iferd, which is made up of more than 3 km of digging. Underground cabling also has advantages, such as the protection of wiring from outdoor exposure (sandstorms, high ambient temperatures, etc.) or aesthetic, which, despite not having an economic impact, it has been taken into special consideration.

Figure 2. Mini-grid layout in Iferd.

Mini-grid design follows the recommendations issued by IEC standards and is fully compatible with a future arrival of the utility grid. For this, despite the electricity supply being single-phase, the distribution lines have four wires, of which three are bonded together (see figure 3). This way, the mini-grid behaves as single-phase two-wire, but it can easily be converted into a common three-phase four-wire simply by removing the bond. Figure 3 also shows the connections of the neutral conductor (N) and dwellings to ground, which constitute the TT grounding configuration[18] used in Morocco and in most of the world. This grounding configuration ensures the protection of users against an electric shock. In these four years, there have been no cases of personal injury.

Electrical installations of dwellings have been paid for by the users and are identical to those connected to the utility grid in Morocco. Each installation includes a 0·5 A residual current device (ground fault circuit interrupter or GFCI in USA), and a 2 meter ground rod. Dwellings are connected to the mini-grid through connecting boxes that include fuses of 2A for power limitation and a low-cost energy meter[19] designed for measuring low power consumption.

Figure 3. Mini-grid topology.

2.3 Costs

The main disadvantage of hybrid systems is that they need high initial investment, which requires the participation of electricity companies, national agencies, etc., and the application of financing mechanisms, such low-interest loans or subsidies[4]. Figure 4-a displays the breakdown costs of the hybrid system installed in Idboukhtir (the Iferd system costs the same removing the diesel generator, i.e., €109,687). It can be seen that the PV modules account for 36% of the component cost (€115,460), but if we take into account the total project cost (€594,000), this proportion is reduced to 14%. This small contribution of modules is, despite the high cost of this particular demonstration project, a common characteristic of decentralised PV rural electrification.

It can be seen that the low-voltage mini-grid is, after the PV modules, the second highest cost. The reasons are its high quality (in comparison to typical diesel grids found in the region; see figure 4-b) and its design, which ensures its compatibility with a future arrival of the utility grid. It is also interesting to note that the cost of the mini-grid is around €600 per electrified dwelling and may increase up to a total of around

€1,000 adding installation costs, which is similar to low-voltage extensions in the utility grid[20].

Figure 4. (a) Component contribution to the system cost in Idboukhtir (€115,460). (b) Traditional diesel grids found in the region.

3. SERVICE MANAGEMENT

The final goal of any energy service is satisfy user demand. In the case of a grid, this goal is normally achieved by the service supplier, which continuously increases the power capacity and operating hours of the generating system. No restrictions are usually imposed on the customers, neither the use of efficient appliances nor an expensive kWh price, and they can consume as much as energy as they want. Stand-alone PV systems could behave in a similar way just by adding more PV modules to the generators. Nevertheless, and mainly for economic reasons, rural systems are conceived and operated as energy-limited systems. This characteristic requires the application of some type of load management, which should balance the satisfaction of users and the continuity of the service in the long-term.

Hybrid village power systems provide an electricity service whose appearance is very similar to that of the grid, which can encourage users to consume a lot of energy and operate less-efficient domestic appliances[17, 21]. Being aware of this risk, the following load management rules were agreed with each village electricity association, before putting the systems into operation, with the purpose of controlling the initial growth of energy consumption: electricity service limited to 14 hours per day, prohibition of several domestic appliances (refrigerators, electric cookers and heaters, etc.) and the obligatory use of fluorescent lamps.

Regarding the latter requirement, we carried out an evaluation of the standard AC market in the nearest city, which permitted us to discover fluorescent lamps with poor cycling resistance or low power factors, but also lamps with a good performance that were recommended to users, which led to the negotiation of a joint purchase from the same dealer. As well as these rules, we fixed an expensive and progressive electricity tariff (see table 2), which penalize high consumption. The only precaution is choosing the tariff prices with care in order to ensure that low-income users can afford satisfactory levels of service.

These initial rules were later modified. First, the service was gradually increased until it achieved a full-time service in December 2003. Second, the use of refrigerators has been permitted since January 2004. And third, electricity tariffs were reduced every year until a minimum of 0·15 €/kWh was reached in 2005 (see table 2). The last two modifications have been, probably, the most difficult decisions taken in the project because, despite their being obviously welcomed by the users, they could compromise the long-term sustainability of the systems. The reason that tips the balance in favour of them was our obligation, as a research institution, to study the operation of the systems with a greater contribution of the diesel generator. Nevertheless, our expectations and those of users were not exactly the same, as commented on below.

Table 2. Electricity tariffs.

In this fee-for-service scheme, each village association pays a maximum of €175 per month, which is credited to a bank account managed by Tichka. The surplus of money collected over €175 remains in the village association coffers, for example, for paying the salary of the person responsible for reading the energy meters and operation and maintenance tasks.

Other possible management schemes, such a flat tariff in which users pay the same tax regardless of their energy consumption, removes the costs of energy meters and service management. Nevertheless, the success of these schemes depends on the goodwill of the users and previous field experiences have not been always satisfactory, even causing confrontations between users and reductions in payments[13].

Finally, it is worth insisting that the purpose of the service management is not selling electricity, which in Morocco is only permitted by the National Electricity Office (ONE), but assessing the willingness of users to pay and checking whether the money collected is enough to ensure, at least, the long-term maintenance of systems.

Concerning the first objective, the good news is that €8,000 was collected in both villages up to December 2005. The bad news is that Iferd inhabitants stopped paying in October 2004, when their financial contribution was €3,475. The reason for this decision is a combination of an internal conflict, the bad operation of their old diesel generator, and they knew that they would be electrified by the national grid, which finally happened at the time of writing this paper, in September 2006. Despite everything, the electricity service was not interrupted.

Regarding the latter event, it is worth pausing here to mention that despite the low-voltage mini-grid and the electrical installations of dwellings being designed to be fully compatible with the grid, only the second grid has been finally reused by the users (the ONE has installed their own low-voltage network and energy meters). Although it is too early to anticipate the future of the hybrid system, we are considering either moving it to an unelectrified village or connecting the PV generator to the grid, although the former option is more probable.

Regarding the second objective, it is worth stressing that the money collected largely covers long-term maintenance costs. After ten years of regular payments, the collected money would reach, in the best case, a maximum of €21,000 per village (€175 x 12months x 10years). For example, the replacement of the expensive stationary tubular battery only accounts for around half of this value.

Nevertheless, the question of who must carry out the long-term maintenance is “a different kettle of fish”. For example, although system reliability is high, an inverter breakdown in Iferd in April 2003 was not repaired for two months, when an engineer with the spare parts was able to travel to Morocco. Such a long time waiting for the repair may attract attention, but it is typical of decentralised rural electrification without local technical support[13, 17, 22]. This example may justify the need for a professional company in the region able to ensure the long-term technical maintenance. The difficulty is that the company may require, for example, a minimum annual turnover of about €100,000 for maintaining three staff and a car[6], which is only affordable in the context of a larger electrification scenario. Following the previous example, around 100 hybrid systems are required at least for this purpose, considering a yearly contribution of €2,000 per system (€1,000 for replacing the battery plus €1,000 to cover the annual turnover of the company). Obviously, this is just an exploratory exercise with a simple hypothesis, but it gives us an idea of the order of the required scale.

4. SYSTEM SIZING: LOAD DEMAND

4.1 Daily load profiles

Figure 5 details the measured daily load profiles as well as the average in both villages after the electricity service was increased to 24 hours a day. These profiles are presented as a function of the normalised parameter p_h, which is defined as the ratio of the output inverter power to that of the nominal inverter (8 kW). It can be seen that the shape of the load power profiles is essentially the same every day. In Idboukhtir, the water pump operated between 12 to 17 hours, which may explain the irregular power consumption in that period.

Average peak loads are around p_h=0·7 and p_h=0·3 in Iferd and Idboukhtir, respectively, but most of the time p_h varies from 0·1 to 0·2, where the reduction of inverter power efficiency is important. For example, the inverter reaches its maximum power efficiency (90%) near nominal power, but the measured inverter energy efficiency in the testing periods was only 79% in Iferd and 55% in Idboukhtir. These poor efficiencies, especially the latter, are caused by the frequent low p_h commented on previously but also because we chose an old inverter, which is very reliable but not very efficient owing to the relatively high no-load losses (around 300W with AC voltage at inverter output).

For inverter energy efficiency calculations it is more suitable to define each daily load profile by means of 24 hourly energy factors, which indicate the daily energy fraction consumed by the load every hour (obviously, the addition of these factors is equal to 1). This way, the same load profile can be used for systems with similar load composition but different sizes. Table 2 shows the hourly energy factors of the average load profiles displayed in figure 5, which are similar to others found in the literature[22,23].

Figure 5. Normalised daily load power profiles (grey lines) and average one (black line). (a) Iferd. (b) Idboukhtir.

Table 2. Hourly factors of the measured average daily load profiles.

4.2 Energy consumption

Families' consumption habits are influenced by innumerable factors, such as composition, ways of life, purchasing power, etc. However, despite the correlation between these factors having its value, the reduced number of dwellings electrified in the project and the difficulty in accessing this information, it leads us to presenting here just the consumption data per dwelling disregarding these factors.

Energy consumption habits are also influenced by the service management commented on previously. For example, during the first 15 operating months energy consumption was strictly controlled, mainly by the application of prohibitive energy prices (see table 1). In this first stage, dwellings used electricity for a basic electricity service (fluorescent lighting, radio and TV satellite) and around 80% of the families consumed less than 300 Wh per day. This energy scenario could have been maintained without changes for a long time, but we decided to remove some restrictions to encourage higher energy consumptions in order to study the behaviour of the hybrid systems near their maximum capacity, being aware that under these conditions systems are usually more prone to failures and blackouts, which could impact service reliability. Despite of these risks, in January 2004, we agreed with village electricity associations the reduction of electricity tariffs and the possibility of using refrigerators.

Somewhat surprisingly, Iferd inhabitants refused the use of refrigerators, mainly because this would suppose a daily operation of their old diesel generator. From 1990, they have learned their own lessons on the disadvantages of the operation of diesel generators and they did not want to return to the same situation. Hence, the experimental cost of recycling their old diesel generator has been high. Surely, we should change it for another new and modern one at the beginning of the project.

Figure 6 details the monthly average daily energy consumption of dwellings in Iferd (all without a refrigerator). It is interesting to see the seasonal nature as well as the continuous increasing in energy consumption, especially in winter months, which reached a maximum of around 600 Wh in January 2006. In this month, the diesel generator and the PV system were operating for 3 and 11 hours per day, respectively. This uncontrolled situation is explained, in part, because the PV energy was free from December 2004 (when the Iferd inhabitants stopped paying) and also due to the imminent arrival of the national utility grid.

Figure 6. Monthly average daily energy consumption of dwellings in Iferd (all without refrigerators).

In contrast, the Idboukhtir inhabitants accepted the use of refrigerators but, more than two years later, only four dwellings have installed them, despite tariffs being reduced again to 0·15 €/kWh to encourage their use. Following the methodology initiated with fluorescent lamps, we carried out a survey of refrigerators that could be purchased in the city and we recommended to users some efficient models whose daily energy consumption was below 1,000 Wh (according to manufacturer datasheets).

Nevertheless, the recorded data detailed in figure 7 show that refrigerator consumption is higher than datasheet specifications (assuming a typical consumption for the remaining domestic appliances). It can also be shown that refrigerators are mainly operated in the summer season and also that identical refrigerators (two lower graphics) may consume very differently depending on their use.

Finally, figure 8 sets out the monthly average daily energy consumption of dwellings in Idboukhtir without a refrigerator. Similarly to Iferd, there is a continuous increase in energy consumption, with a maximum of around 500 Wh.

Figure 7. Monthly average daily energy consumption of dwellings with refrigerators in Idboukhtir, including their capacity and daily consumption according to the manufacturer's specifications.

Figure 8. Monthly average daily energy consumption of dwellings without a refrigerator in Idboukhtir.

5. CONCLUSIONS

Experience acquired during more than four years with a pilot electrification project carried out in Southern Morocco has been presented in this paper with the aim of divulging lessons that can be useful in designing, managing and sizing small PV-diesel hybrid village power systems.

Regarding the system design:

1. In small systems, a one phase supply avoids the problem of unbalanced loads and does not prevent the use of three phase motors, which can be operated using standard frequency converters.

2. As pre-electrification, the low-voltage mini-grid and the indoor electrical installations of dwellings can be designed to be fully compatible with the grid and can be reused in case of a future grid connection.

3. The extension of the utility grid is a general problem not only for the hybrid systems but also for other applications, such as PV pumping. Affected systems can be, for example, either moved to another site or incorporated into the grid making a grid-connection of PV generators.

Regarding the service management:

4. Acquired experience in this small scale project is difficult to extend to larger electrification programmes. Despite this, users seem very satisfied with a full-time AC electricity service and they are willing to pay for it.

5. Money collected may cover long-term professional maintenance for a medium-scale programme (of the order of tens of systems).

Regarding the sizing of systems:

6. Energy consumption is strongly correlated with electricity tariff rates. When the latter are similar to those of the grid (€0·15 per kWh), families daily consume an average of 500 Wh for a basic electricity service (lighting, TV and radio).

7. Even with an affordable electricity tariff, most of users do not want to pay for (or cannot afford) a refrigerator. The few refrigerators installed are operated only in the summer season and show daily energy consumptions, of over 2,000 Wh, which largely exceed the manufacturer specifications. This suggests a more exhaustive control be carried out before permitting their use.

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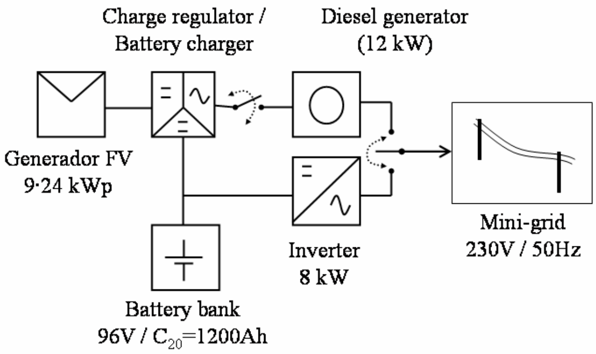
(a)



(b)

Figure 1. (a) Idboukhtir village system. (b) Switched topology.

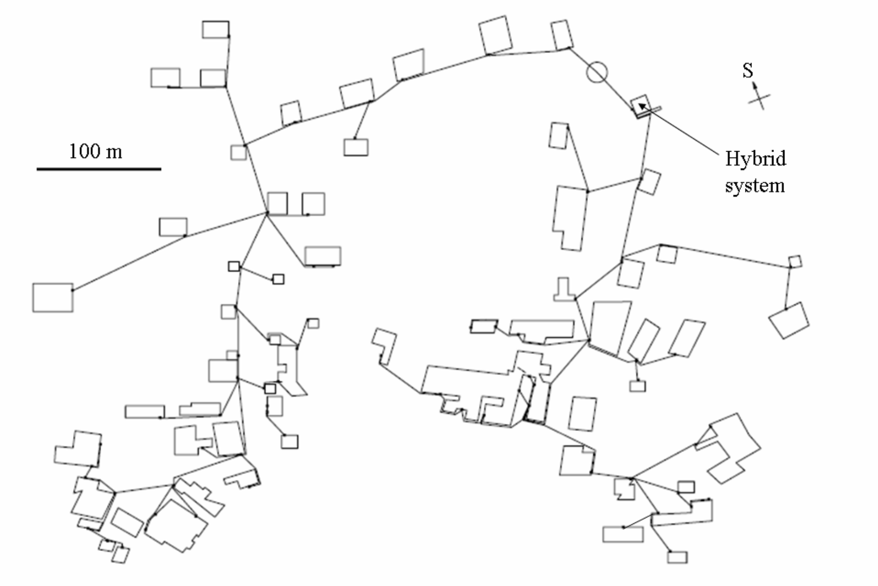


Figure 2. Mini-grid layout in Iferd.

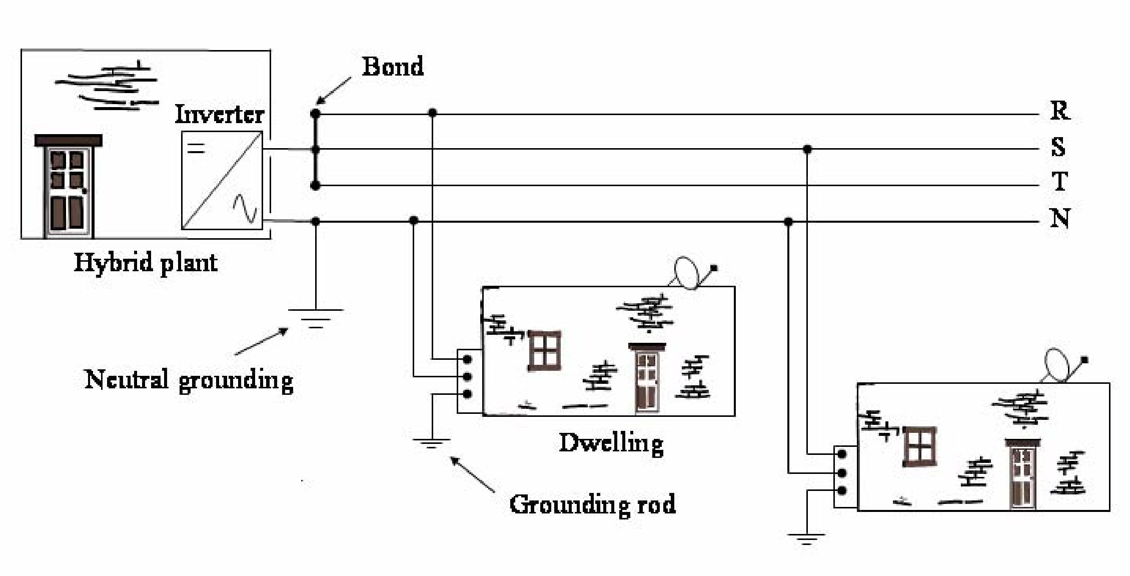
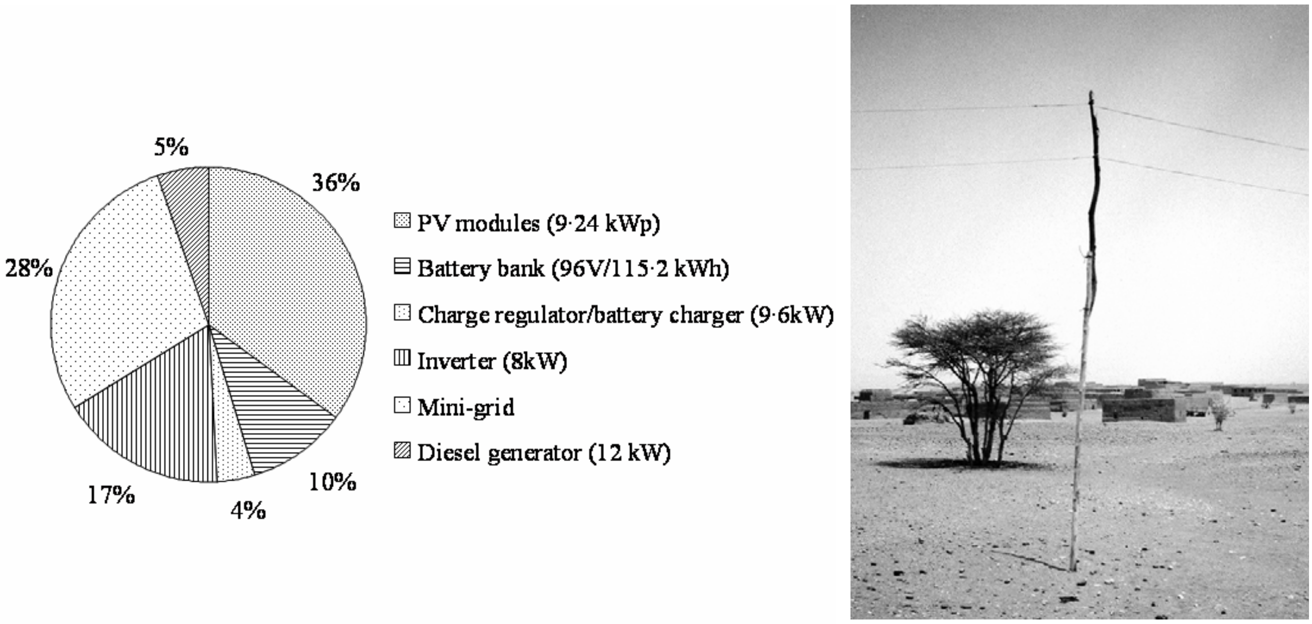


Figure 3. Mini-grid topology.



(a) (b)

Figure 4. (a) Component contribution to the system cost in Idboukhtir (€115,460).

(b) Traditional diesel grids found in the region.

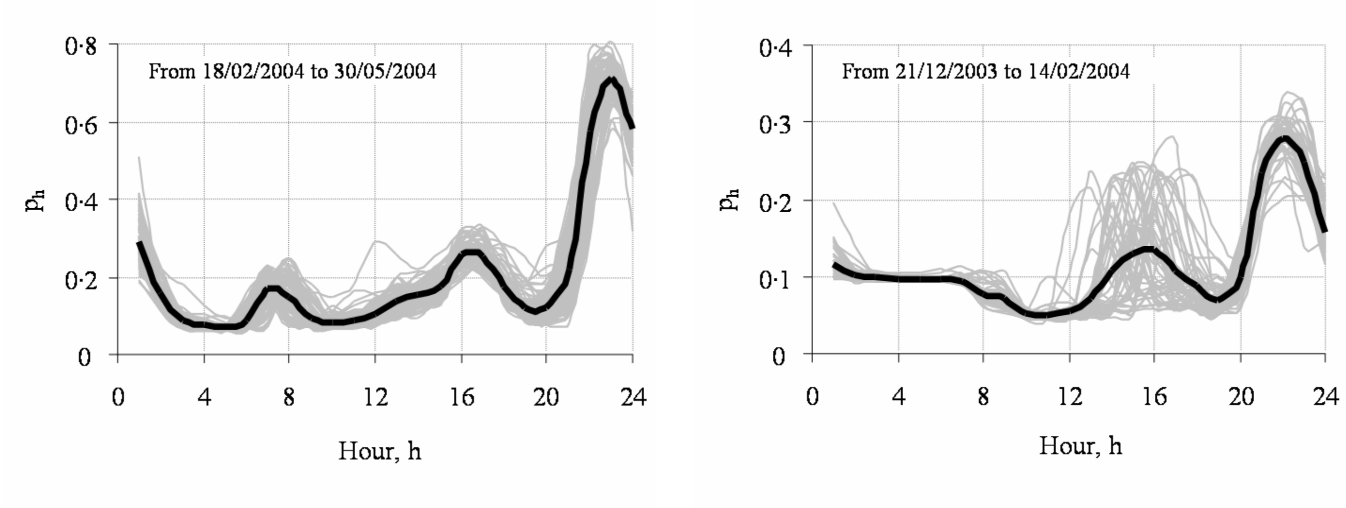


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Figure 5. Normalised daily load power profiles (grey) and average one (black).

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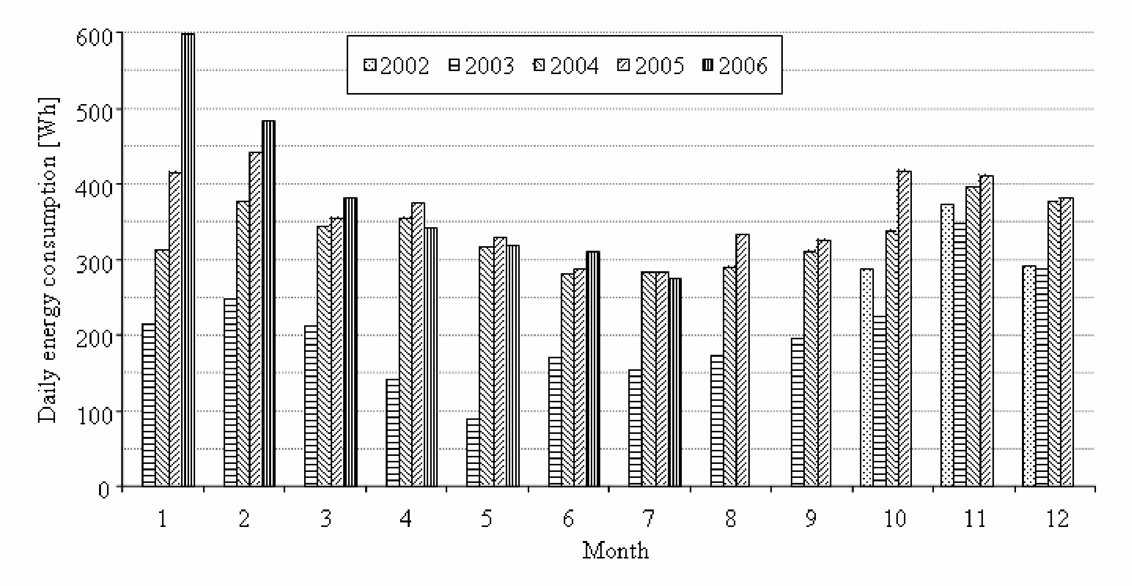
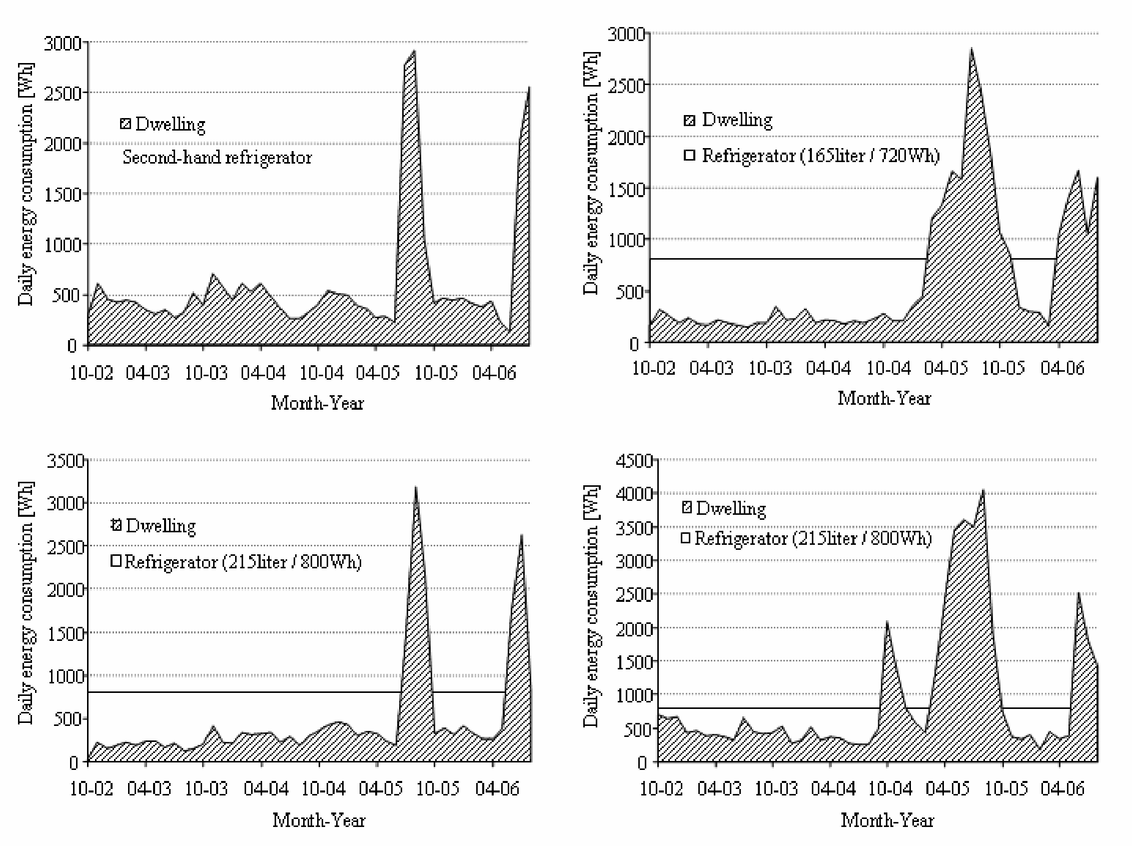


Figure 6. Monthly average daily energy consumption of dwellings in Iferd (all without refrigerators).



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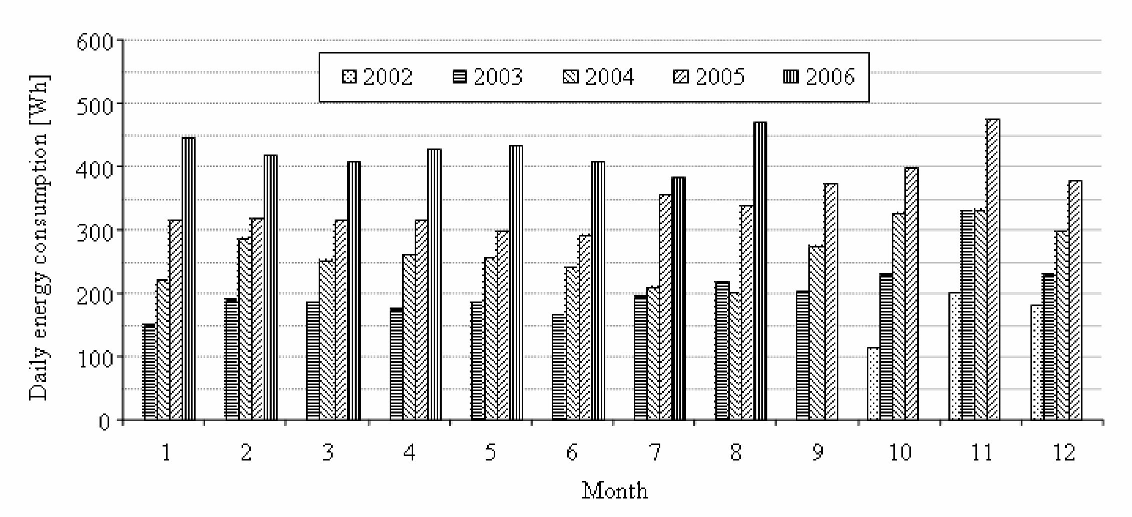

Figure 8. Monthly average daily energy consumption of dwellings without a refrigerator in Idboukhtir.

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Years					
2002-2003		2004		2005	
Fixed tax: 1·5 €/month		Fixed tax: 1·5 €/month		Fixed tax: 4 €/month (first 10 kWh included)	
Monthly consumption [kWh]	[€/kWh]	Monthly consumption [kWh]	[€/kWh]	Monthly consumption [kWh]	[€/kWh]
≤ 10 > 10 and ≤ 17 > 17	0·35 0·50 1·00	≤ 10 > 10 and ≤ 40 > 40	0·35 0·50 0·60	> 10	0·15

Table 1. Electricity tariffs.

Hour	Iferd	Idboukhtir	Hour	Iferd	Idboukhtir	Hour	Iferd	Idboukhtir
1	0·058	0·043	9	0·019	0·027	17	0·051	0·040
2	0·032	0·038	10	0·017	0·019	18	0·036	0·032
3	0·018	0·036	11	0·018	0·018	19	0·025	0·025
4	0·015	0·035	12	0·021	0·020	20	0·024	0·036
5	0·014	0·035	13	0·027	0·026	21	0·045	0·085
6	0·018	0·035	14	0·031	0·039	22	0·117	0·102
7	0·034	0·035	15	0·036	0·047	23	0·144	0·091
8	0·030	0·029	16	0·052	0·049	24	0·118	0·058

Table 2. Hourly load factors.