WISE lecture series
Monday, October 1st 2012, University of Waterloo

Hybrid photovoltaic power systems and rural micro grids: lessons learned and case studies in developing countries

Xavier Vallvé

- Trama TecnoAmbiental, Barcelona,Spain –

xavier.vallve@tta.com.es

Trama TecnoAmbiental (TTA)

- SME Founded in Barcelona en 1986
- Independent Consultants in distributed Renewable Energy
- Consultancy, engineering, research, project management, social aspects, financial, …
- Since 1989: Off-grid rural electrification practitioners
- Design and Project management of RE-hybrid micro-power plants and micro grids for rural electrification in southern Europe, Africa, Latin America, Oceania …

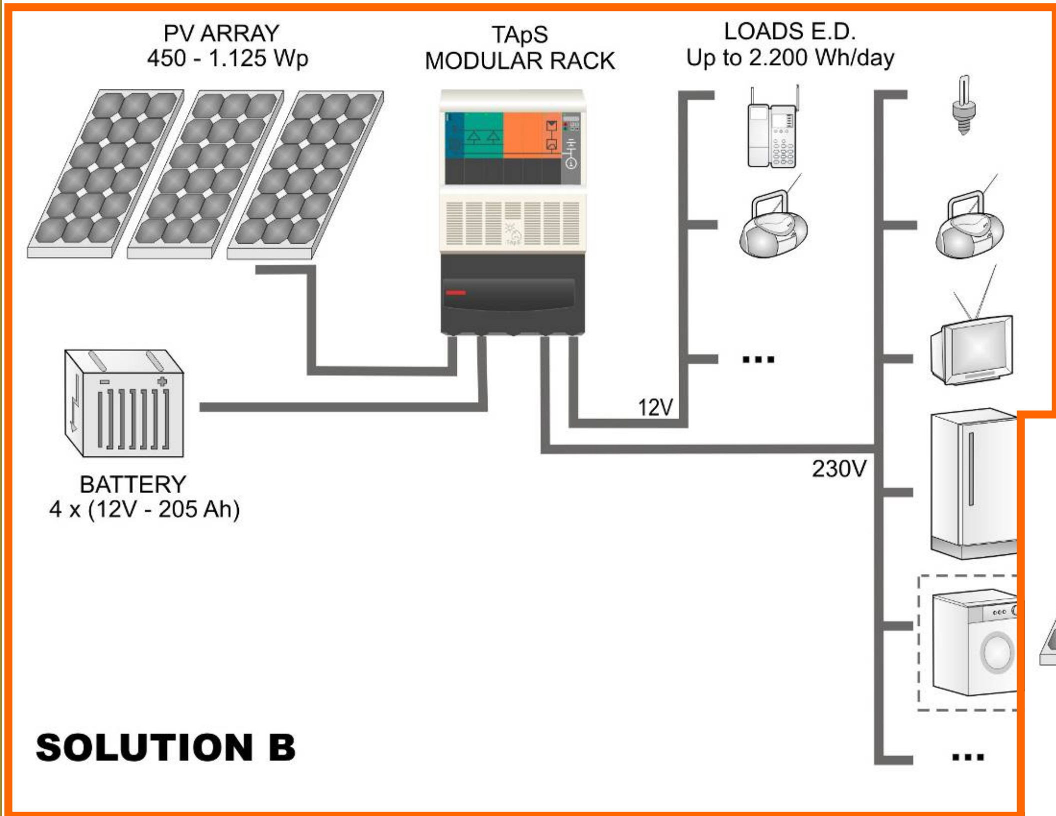
Member of:

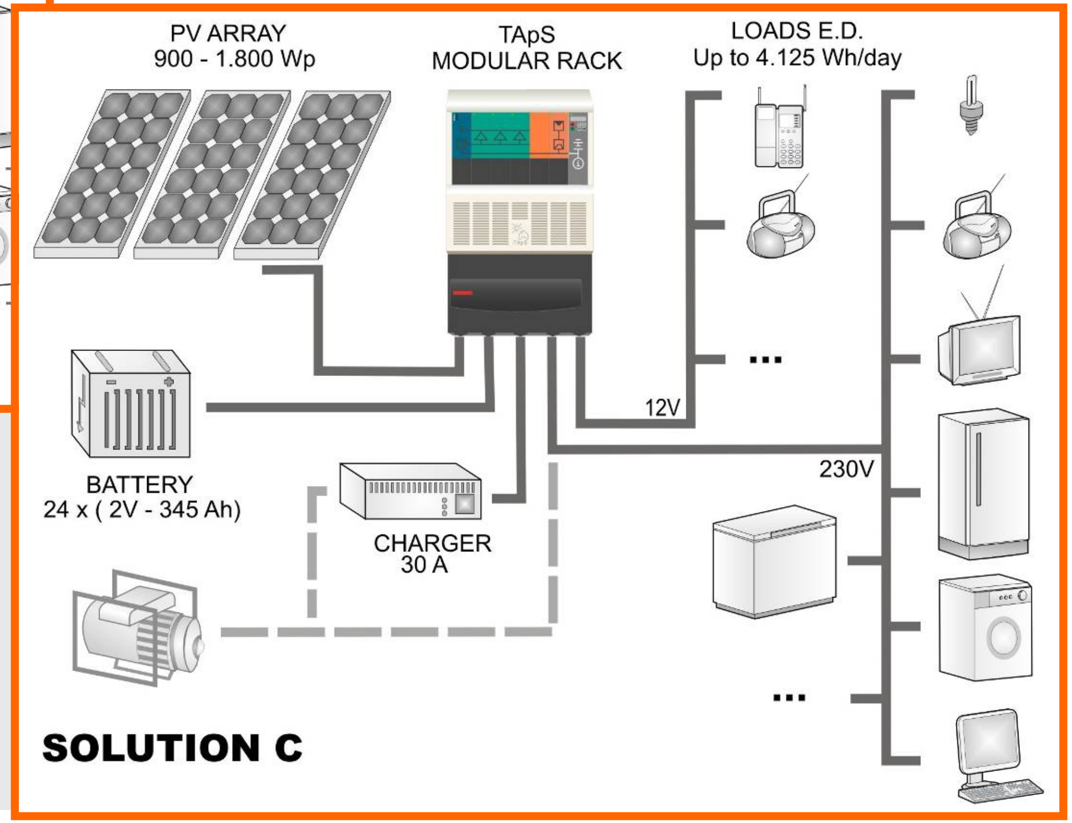
Alliance for Rural Electrification

solartys

Asociación Española para la Internacionalización y la Innovación de las Empresas Solares

Reference: individual autonomous hybrid power plant layouts in Southern Europe





Example Solution C

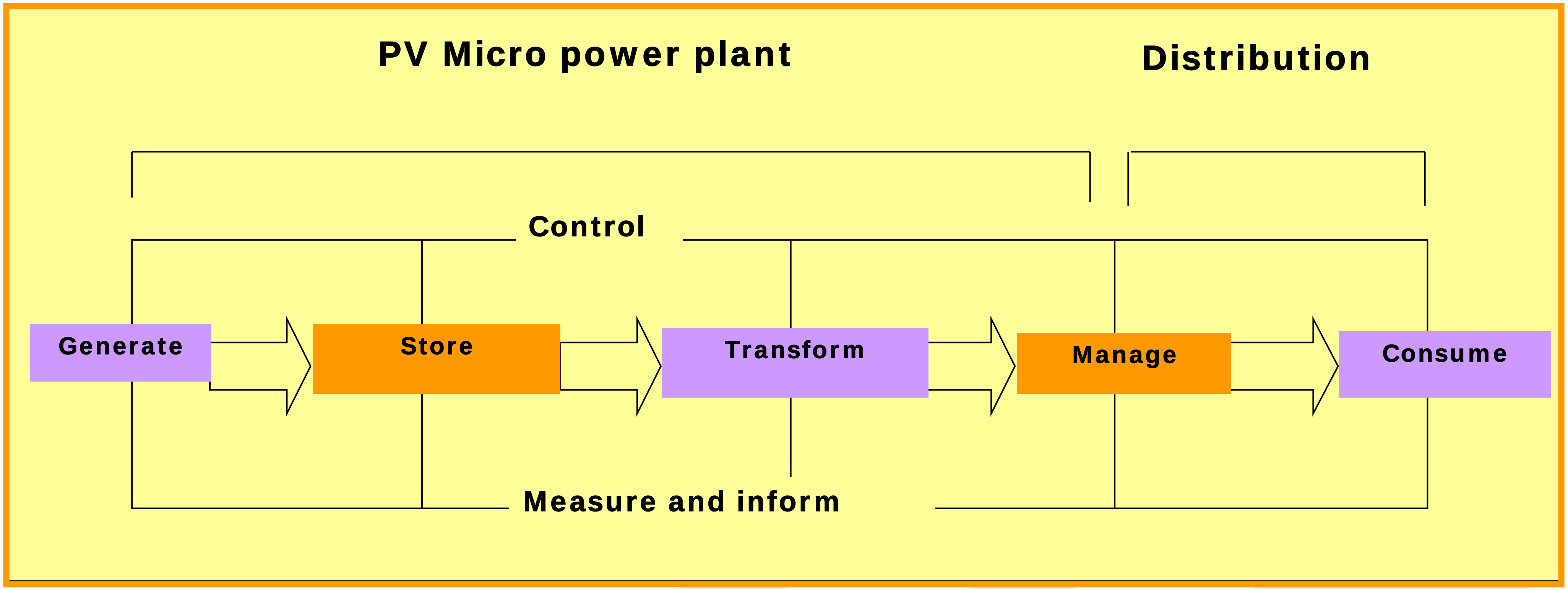
Pyrenees, Spain

Example rural micro grid

Andalucía, Spain

From interim to permanent solutions

Main functions in a RE micro power plant



From individual PV hybrid autonomous power plants to micro-grids

Application types	Types of uses
Home applications	Lighting Audio/video Refrigerator Small household appliances Washing machine Irons Freezer Odd jobs
Public areas applications (places of collective life: worship halls, community centre, health centre, etc.)	Similar to above and more powerful. Street lights. Village water pumping.
Economic activities applications	Process equipment supply (mainly motors)

Individual PV micro plants in Europe

Multi-user micro grids (MSG) in Developing Countries

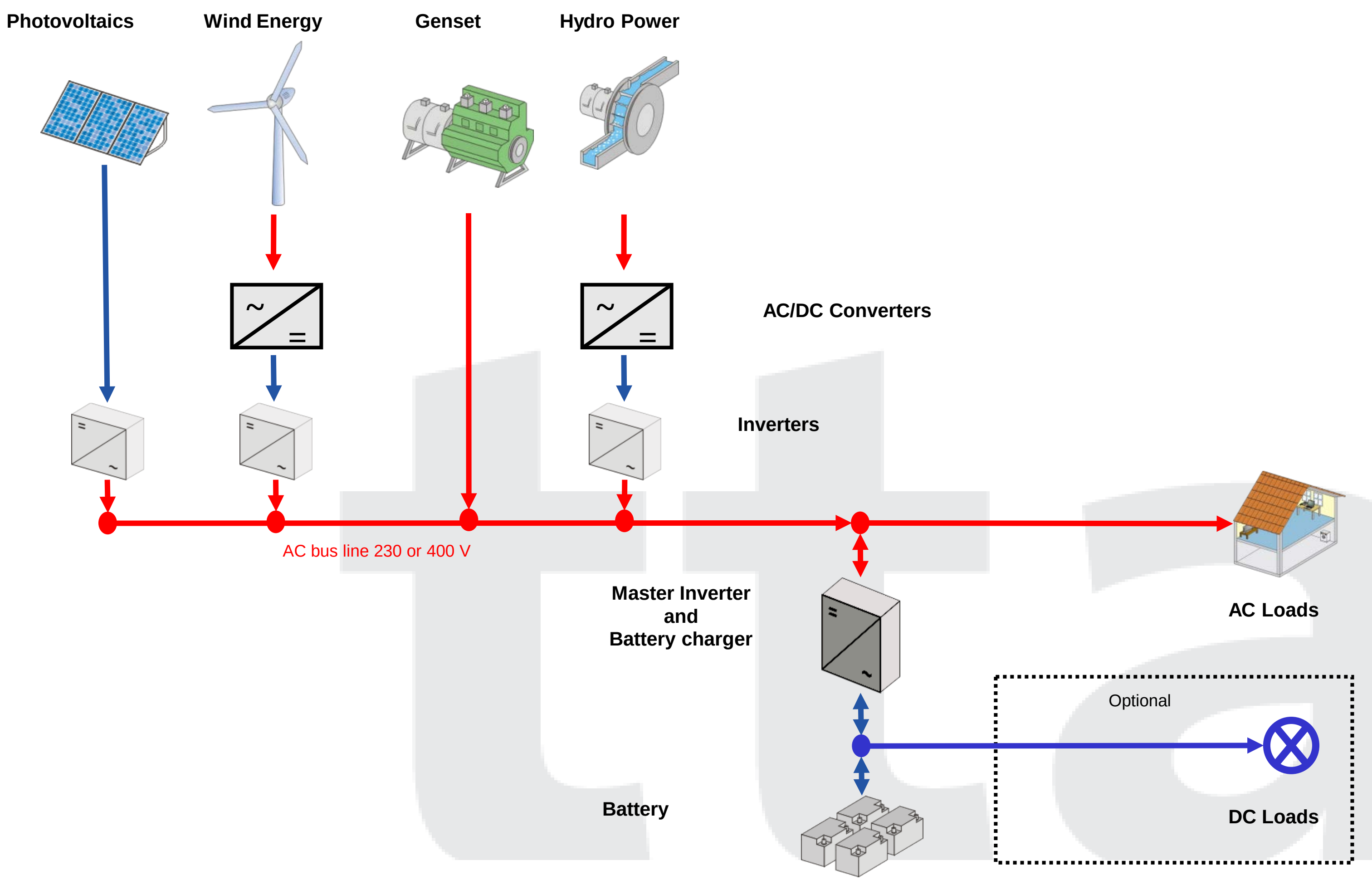
Structure of Hybrid Micro power plants-AC coupling

All electricity generators are connected to the AC line.

AC generating components may be directly connected or may need a AC/AC converter to enable stable coupling.

A bidirectional master inverter controls the energy supply for the AC loads and battery charging.

DC loads can be optionally supplied by the battery.

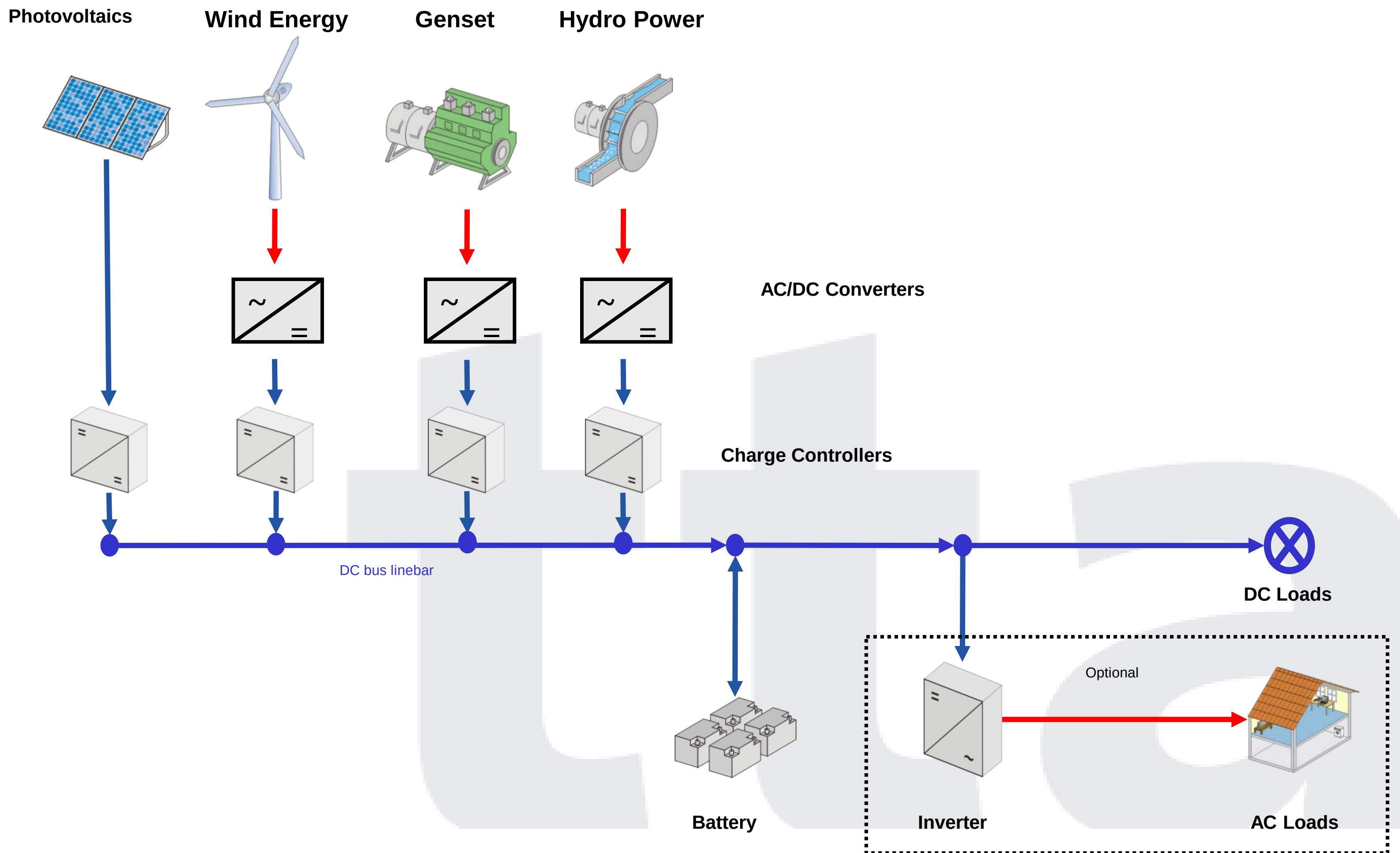


Structure of Hybrid Micro power plants-DC coupling

All electricity generators are connected to a DC bus bar from which the battery is charged.

AC generating components need an AC/DC converter.

The battery, protected from over charge and discharge by a charge controller, supplies DC loads and AC loads through the inverter.



STATE OF THE ART: Typical Design approach

- Renewable Energy hybrid micro-power plants and micro-grids capacity up to 100 kW and LV - AC distribution grid
- Need complementary R&D and feedback from identified needs in rural areas of southern Europe, Africa, Latin America, Pacific ...
- Present technical specifications and best practices developed mainly from Pilot Projects, IEC technical specifications, IEA PVPS Task3 and Task11 recommended practices, etc
- Demand analysis, segmentation and management is a key issue
- Technical solutions with high RE penetration (>70%) are a challenge because the intermittence of energy generation
- Technology adapted to implementation schemes based on long term service horizon with local operator and local capacity building
- Monitoring of facilities to validate technology and the service

STATE OF THE ART: Standardized Typical Design

- DC, AC or combined coupled, mainly Renewable Energy generation
- Power plant bus-bar voltage: < 75V DC (SELV)
- Battery: Pb-tubular, vented, DOD_{max}=75%, A>3 days, 48V
- RE Charge controller: PV-MPPT; WG-PWM; etc
- Inverter: sinusoidal bi-directional η> 85%
- RE generators: PV modules, Wind turbines, Pico hydro, ...
- Data logging: performance indicators based on IEC 61724
- Electrical supply to loads: Mainly standard AC quality single phase
- Load Management: user interface, automatic load disconnect
- Etc.

Comparison of PV Individual and Micro Grids

Technology	Advantages	Shortcomings
Small RE individual plants 	• High flexibility. • Easy to move and share. • Consumption user managed on a day to day basis	• Limited to their specific use. • Maintenance / repairs not safeguarded. • Limited surge power capacity. • Monitoring individual plants can be expensive and difficult.
Multi user Solar Grids (MSG) 	• Improved quality (surge power, load shedding, 24 hr supply, etc) • Efficient and cheaper maintenance • Easily expandable • Lower investment for compact villages. • Telemetry can be economic for monitoring plant's status.	• If no backup: Shortages in case of unfavourable weather conditions affect everyone. • If genset backup: functioning depends on availability of fuel • Social rules required to distribute energy availability. • Local management required.

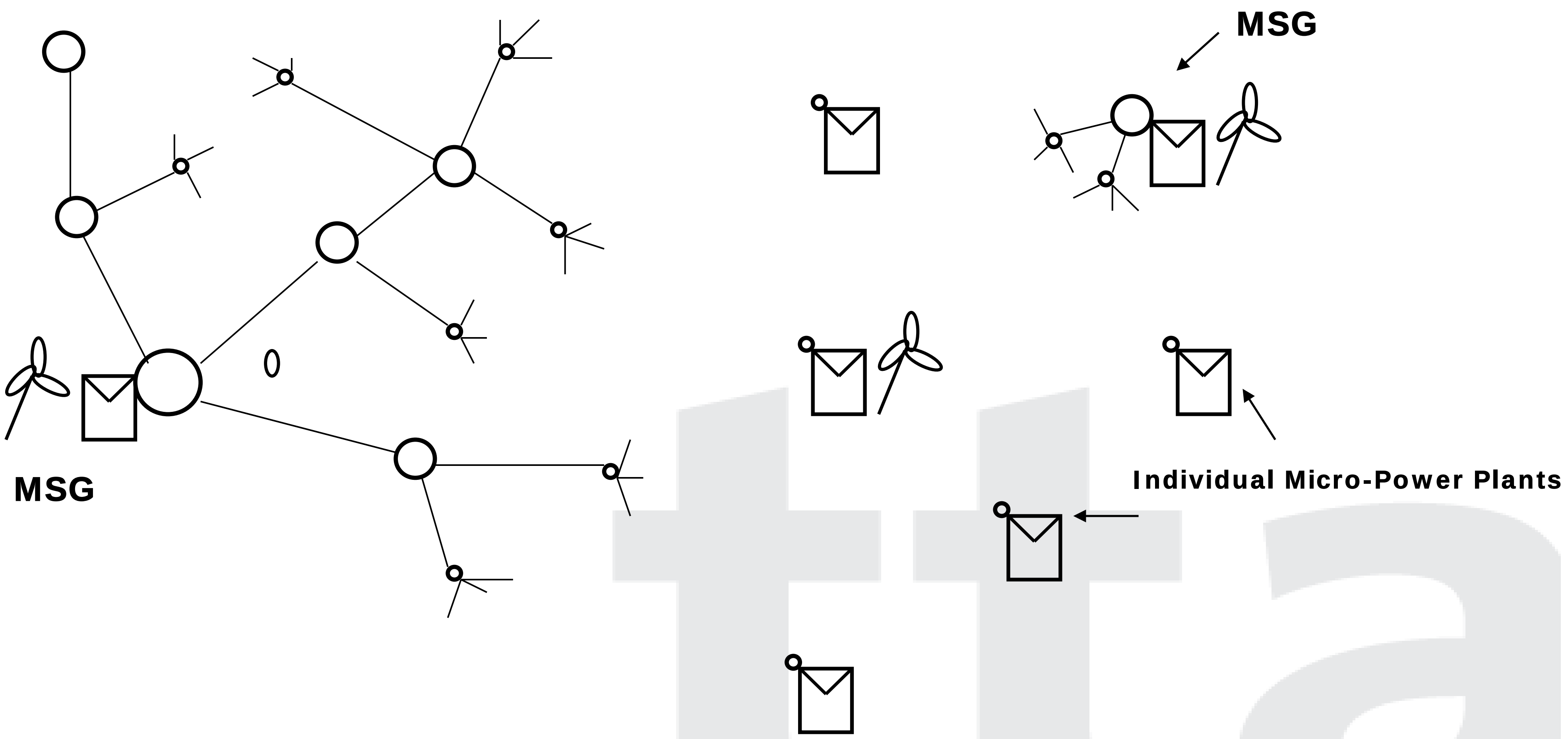
➢ **<u>Challenge:</u> sharing the energy available without conflicts**

➔ **Energy distribution and metering issue!**

Universal electricity access: current situation in DC

- Low population density and low demand in electricity
- Remoteness thus high costs of grid extension and connection
- High losses on transmission lines and high operation and maintenance costs
- Lack of adequate regulation/business models for decentralized electrification

VISION: Universal electrification-individual plants and micro grids under one operational scheme

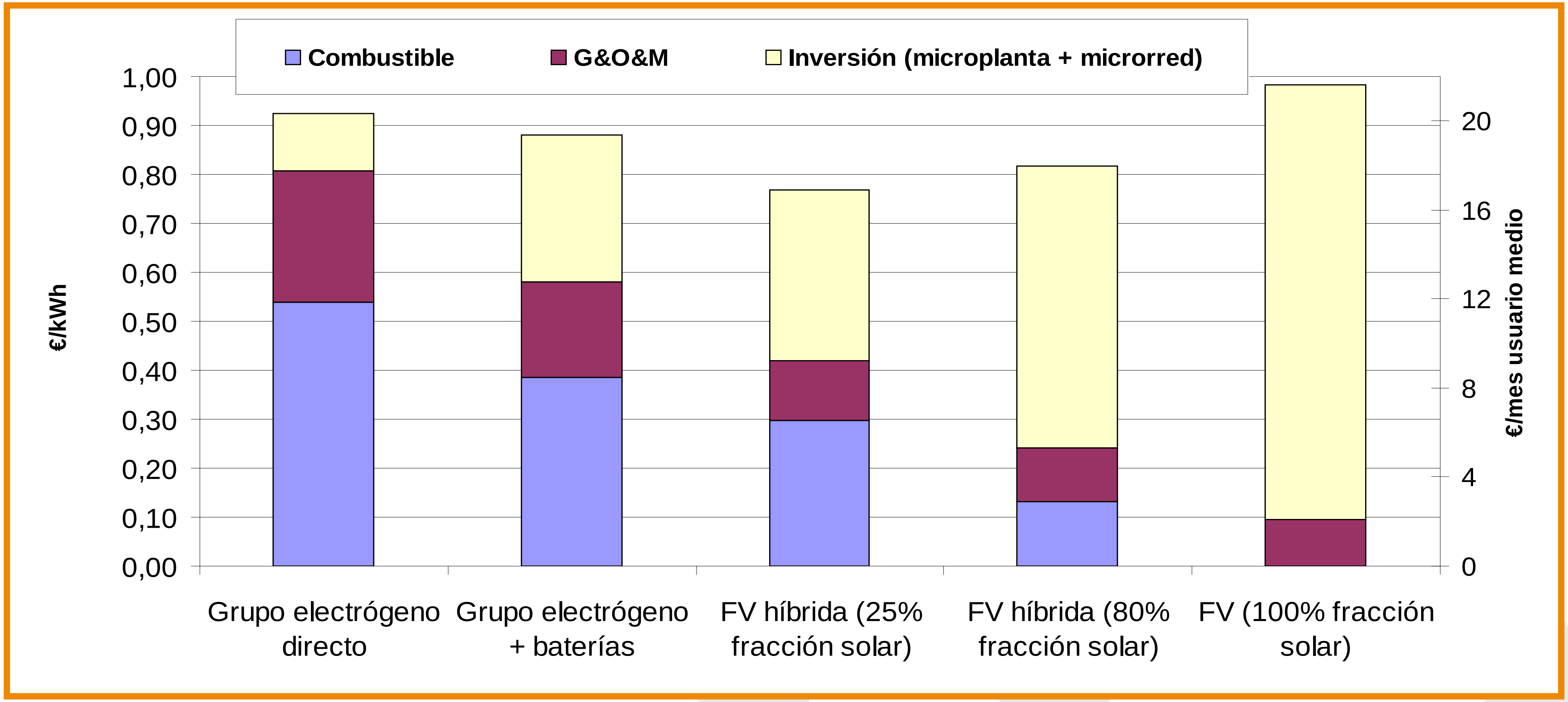


Micro-grid with Solar Generation (MSG) – definition -

- A combination of different but complementary energy generation technologies based on renewable energies or mixed (RES + genset)
- Steady community-level electricity service, such as village electrification, offering also the possibility to be upgraded to either more capable systems or through grid connection in the future
- Total installed capacity up to 100 kW (according to IEC)
- Distribution line in Low Voltage (up to 1.000V) (only distribution)
- Single or 3-phase grid

PV Hybrid Mini Grid in West Bank, Palestine

RE Hybrid micro grids more sustainable than fossil fuelled Gensets



Levelized costs for PV and Diesel technologies in microgrid for 340 users in Peru (D.R. 5%, Diesel: 1 €/l)

Source: http://www.esmap.org/filez/pubs/620200785630_Peru_Solar-Diesel_Amazon_111-07.pdf

DEMAND SEGMENTATION

We group the households according to Energy Daily demand because this also defines the load profile.

	Category A	Category B	Category C
Type of use	Individual basic "very low and low energy consumption" (lighting and audio/video).	Individual medium services (same as category 1 + freezer or refrigerator and appliances) Or community services (health care centre: lighting and freezer, etc.)	Individual high services (same as category 2 + washing machine, vacuum cleaner, small tools, etc.) Or public lighting
Essential consumption characteristics	•Low number of receivers •Low power of receivers •Slim rigid load profile (P1)	•Medium number of receivers •Receivers more powerful •Slim rigid and base load profiles (P1+P2+P3) •or Multiple basic users (P1+P1+ .. n)	•High number of receivers •Some receivers are powerful •High instantaneous power inrush •"Variable" load profile (P1+P2+P4+P5) •or Multiple users (P1+P1+P2+ .. n)
Probable hourly avg power	$Pn \leq 50$ W	0,1 kW < Pn < 1,5 kW	0,3 kW ≤ Pn < 3 kW
Probable surge power	$Ps = 100\ W$	$Ps = Pn + 1\ kW$	$Ps = Pn + 2\ kW$
Average daily energy demand	$E \leq$ 550 Wh/d	$E \leq$2,2 kWh/d	$E <$ 5 kWh/d

Monitoring

Combination of user questionnaires and data logger

- **User records:**
  - **Satisfaction ??**
  - **Electrolyte level in battery**
  - **Black outs ?**

Data logger:

built-in device in power conditioner

Hourly Data Storage (1 year):

Average and total hourly values

Parameters:

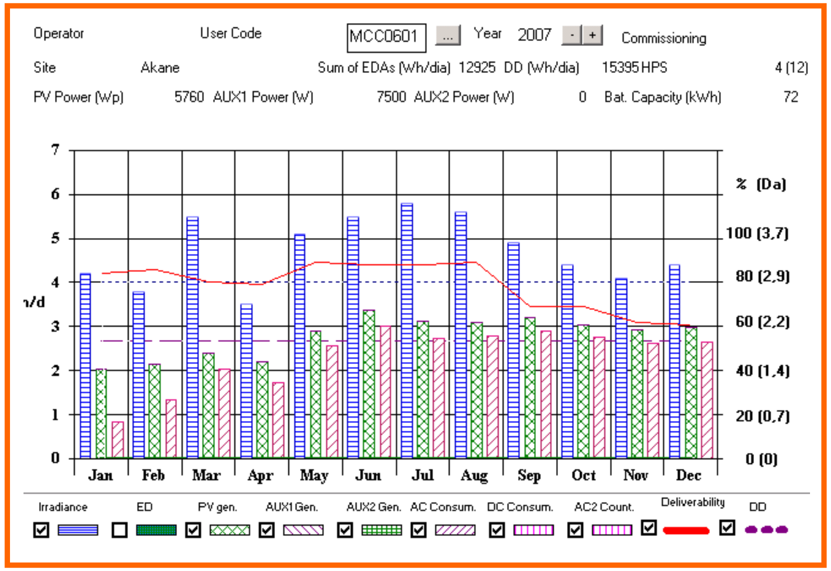
all relevant energy flows

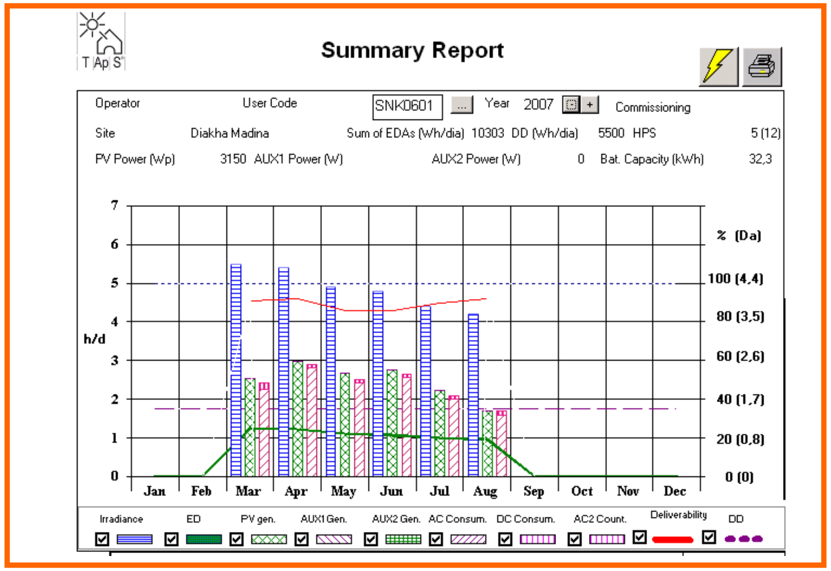
solar irradiance

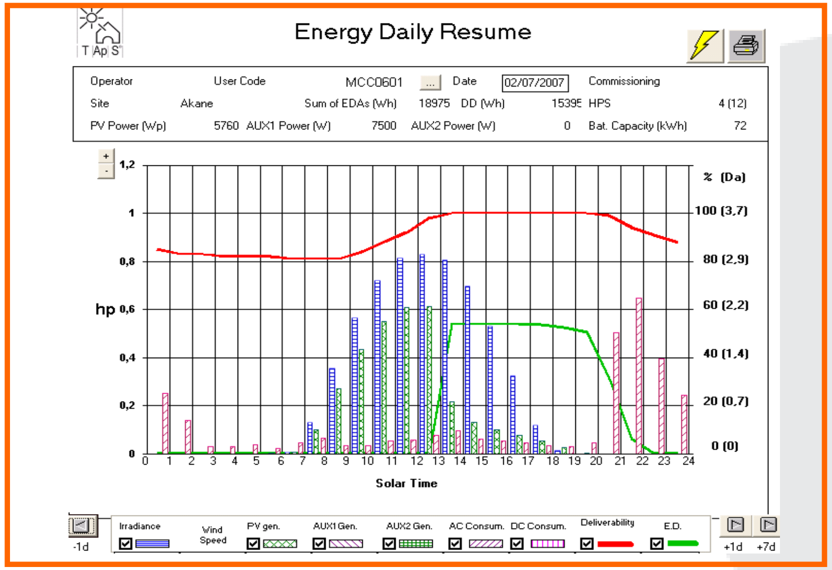
information on battery (voltage, SOC, etc.)

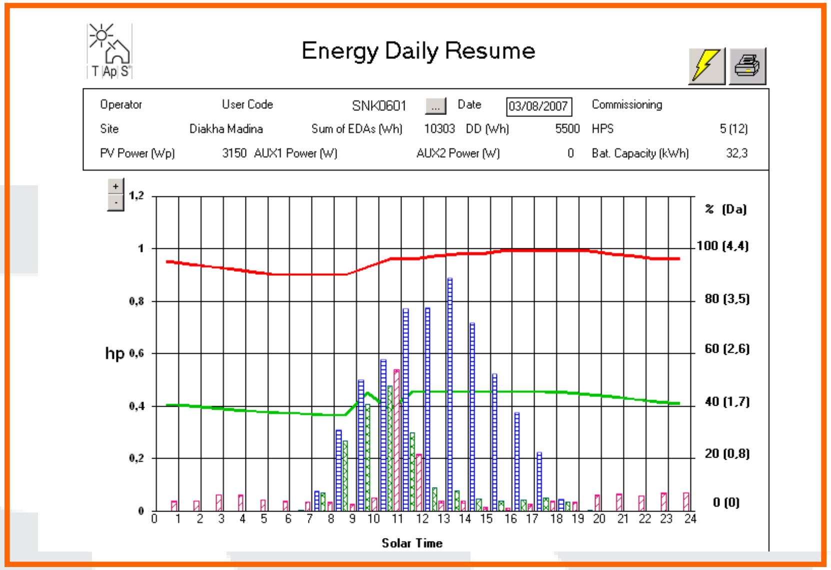
others

Typical monitoring data









Some relevant critical issues for RE Rural microgrids

- **Ownership and management scheme**
- **Load management, invoicing and tariffs**
- **Future expandability and interconnection**

Business models for rural electrification

Financing Policies

Legitimate public investment needed (could be reduced in the long run)

Need of tailored tariff schemes

Administrative adapted scheme: Challenges at the local level

- Local ownership determines whether projects are successful.
- All stakeholders, community leaders, companies, aid organisations and public authorities have to work together. Definition of the key roles.
- It is essential to define the **managing models** ensuring:
  - Responsibility clear definition
  - O&M service.
  - collection and managing of the incomes.
- Capacity building activities.
- Users have to be educated about the possibilities and limitations of their service and to use it rationally.

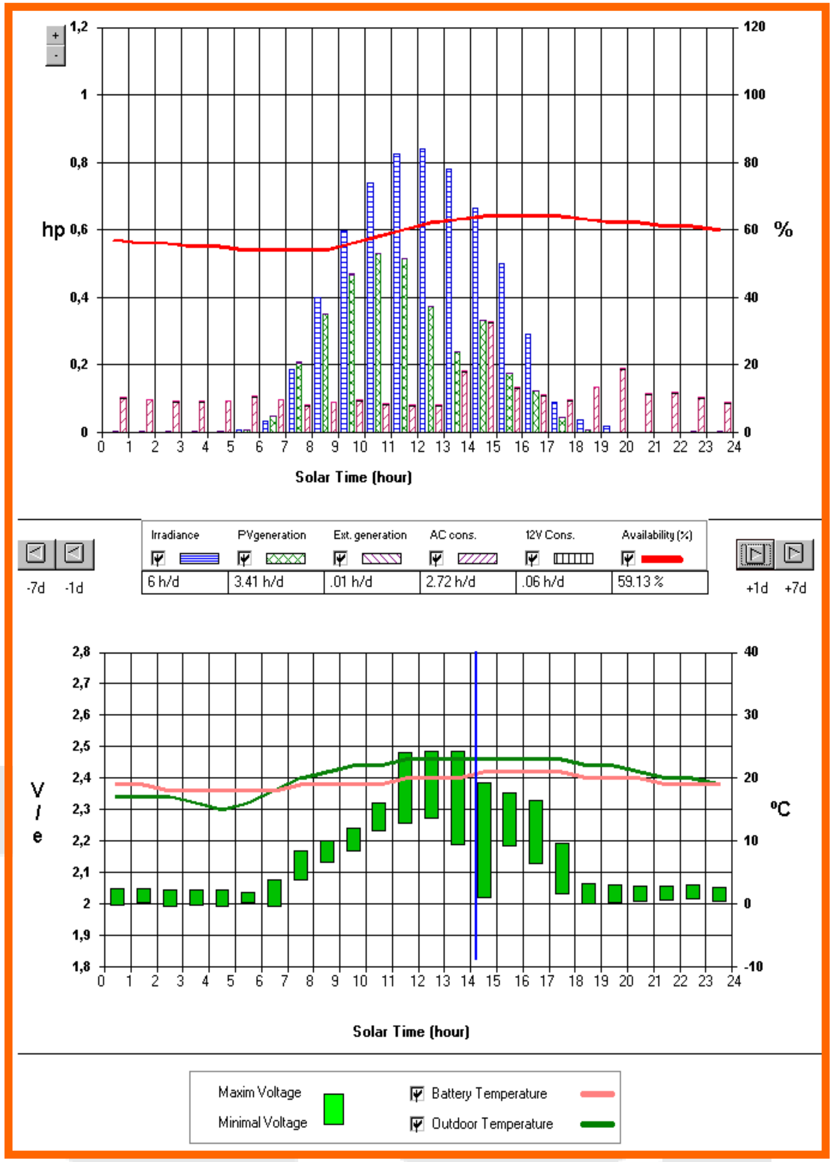
Business models for rural electrification

- Community based
- Private sector based
- The utility based
- Combination of the above

Interest for load management in PV powered micro-grids

Strategies of load management:

- Disconnect loads to protect the battery: traditionally based on battery voltage. But this does not provide adequate information to user
- Find and try to eliminate parasitic stand-by loads: the most important and difficult ! Undetected by performance indicators !
- Time shift deferrable loads to only sunny days: Battery SoC is higher... battery could be smaller...
- Time shift deferrable and ballast loads to surplus energy status: PR is higher... generator size could be smaller; HBI is higher... longer battery life, better autonomy



Load related challenges in rural microgrids

1. **Social Aspects:**

   - to identify the users' energy needs and to ensure a resource distribution without conflicts

2. **Individual energy demand management :**

   - to incentivize the consumption during surplus RE generation periods
   - to manage each user's energy in an independent way
   - to guide users' energy consuming habits to optimize energy management

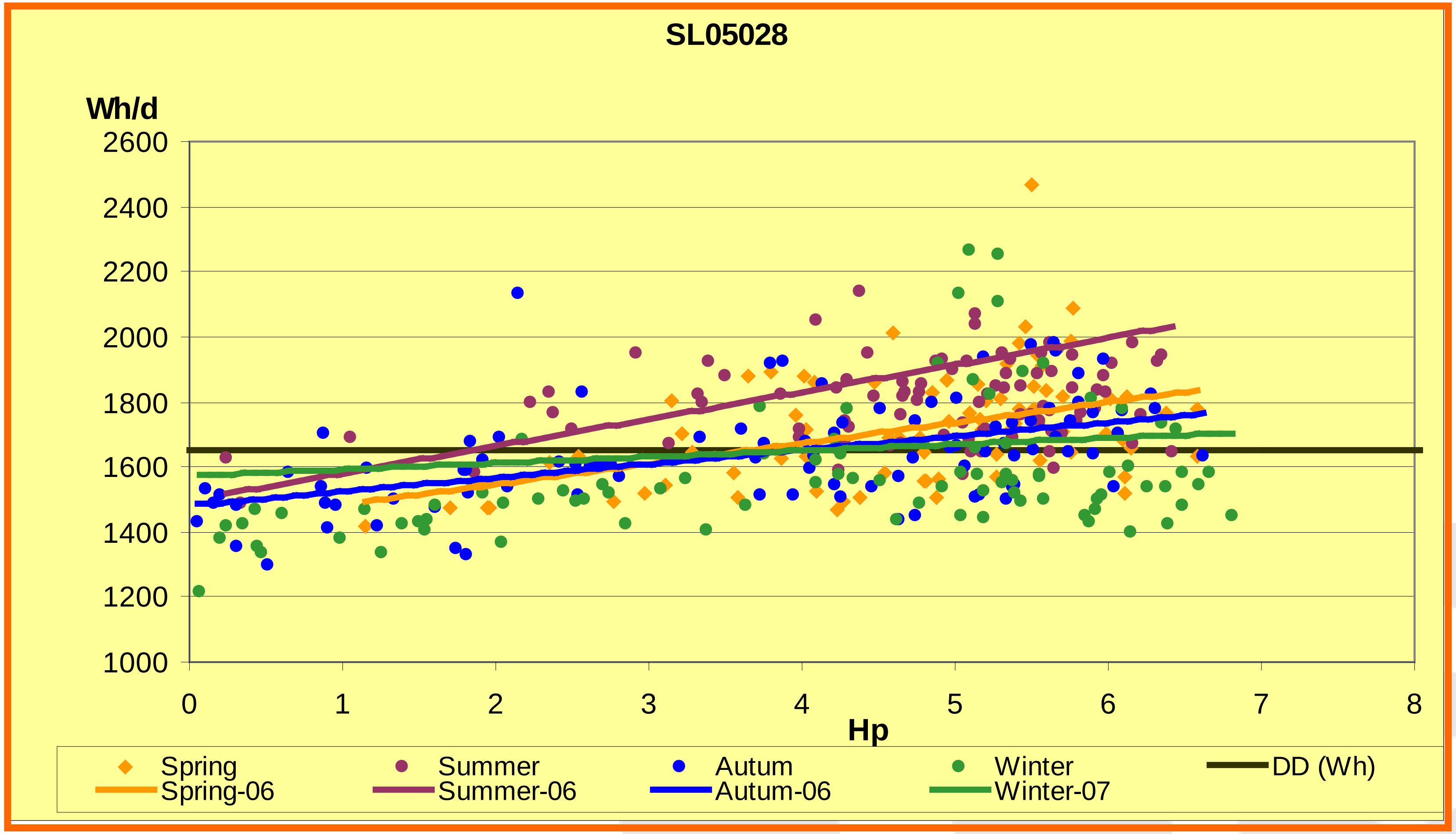
3. **Techno-economic long term sustainability:**

   - to reduce uncertainty on invoicing and unpaid fees
   - to ensure that batteries, inverters etc. will operate within design range

Load management issues

- User information interface + training
- Automatic total load disconnect
- Automatic selective load switching
- Individual Energy Daily Allowance (in micro grids)

RESULTS OF LOAD SENSITIVITY BEHAVIOUR (careful user: good operator)



Energy Daily Allowance (EDA)

- Traditionally in conventional grid connection: users pay for consumed kWh
- In autonomous electrification with RE: Key aspect is the constrain on available energy
- In RE electricity, user should pay for availability not for the consumed energy
- Tariff based on the **Energy Daily Allowance** (fee for service ≠ prepayment)
- Clearer and easier financial planning for operator and for client
- It reduces transaction costs

Electricity Dispenser / meter

Single phase electric meter with dispenser functions

Main Current Switch (40A):

- Energy Daily Allowance (EDA) management according to the contracted tariff
- Virtual storage of saved energy: 3+3*EDA
- Programmable power limitation

Auxiliary Smart switch (5A) :

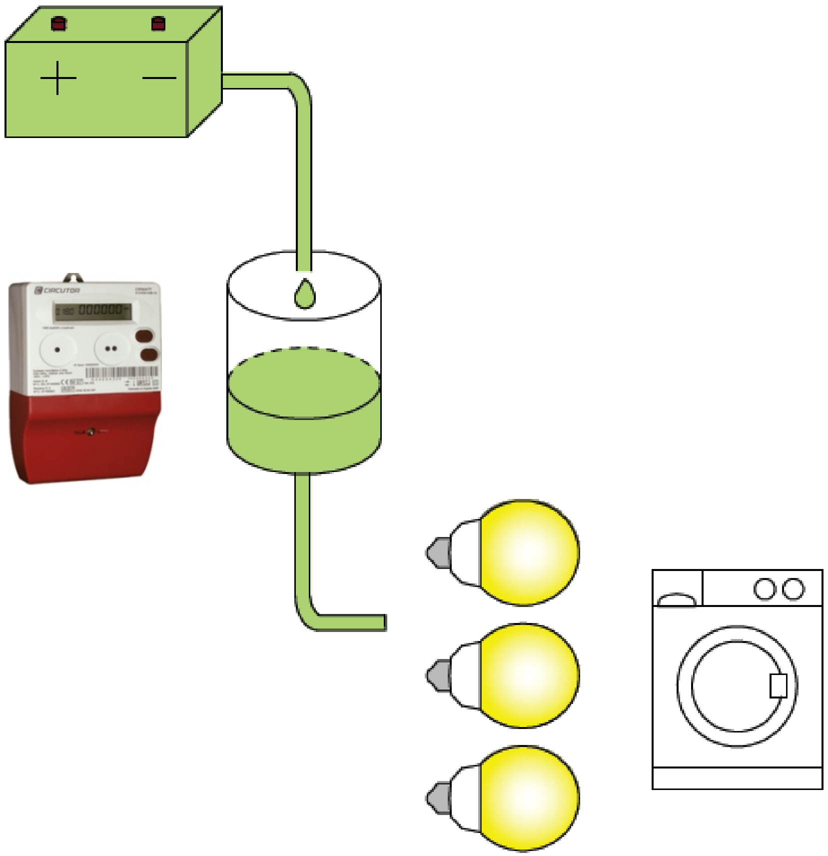
- for deferrable loads

Smart RFID card for:

- Tariff management
- Invoicing management

- **Certified energy meter**

Electricity Dispenser / meter
The EDA algorithm



As an analogy, we can imagine the **dispenser** as a buffer water tank

The tank gets a constant trickle inflow from the micro-grid proportional to the contracted **energy daily allowance**

The tank empties as energy is consumed

When the consumption is equal to the fill up rate we are in balanced consumption

The tank has a capacity equivalent to 3 days of **energy daily allowance**

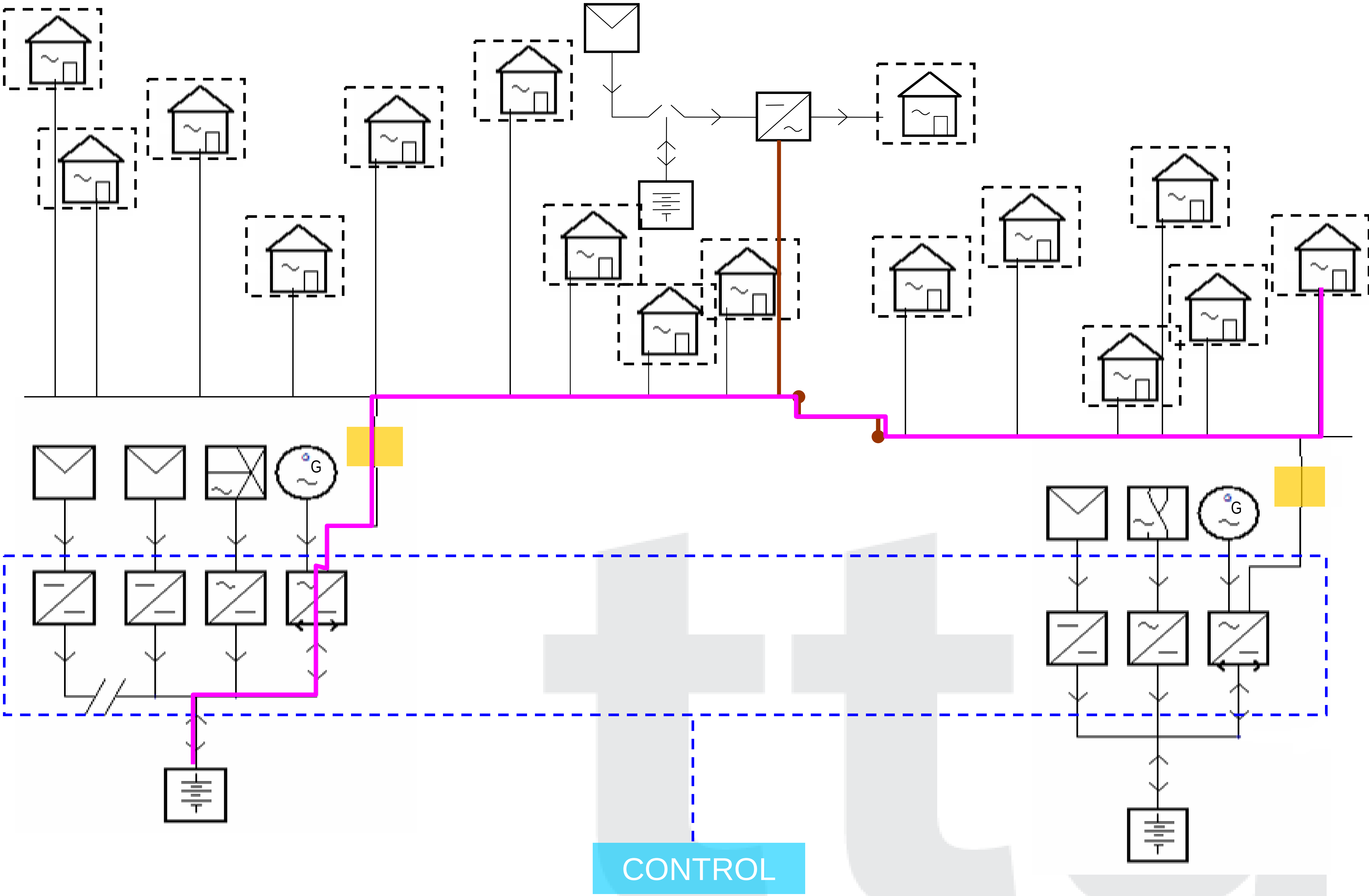
You can use this energy anytime but you cannot store more units than the tank's capacity

modes of operation

- Modbus RS485 communication with the central plant supervisory control
- Demand management in indication according to energy status in PV plant

Mode	Description	Factor	Activation
Normal	EDA and power to rated values	1	Energy in the in the microgrid is between normal values
Bonus	Consumed energy price lower than "normal" price	0,5	PV MPPT is curtailing
Restriction	Consumed energy price higher than "normal" price	2	Battery state of charge is low
Power Limitation	Reduced Maximum power limit	0,8	Inverter Power output is lower than contracted value

Future expandability and interconnection

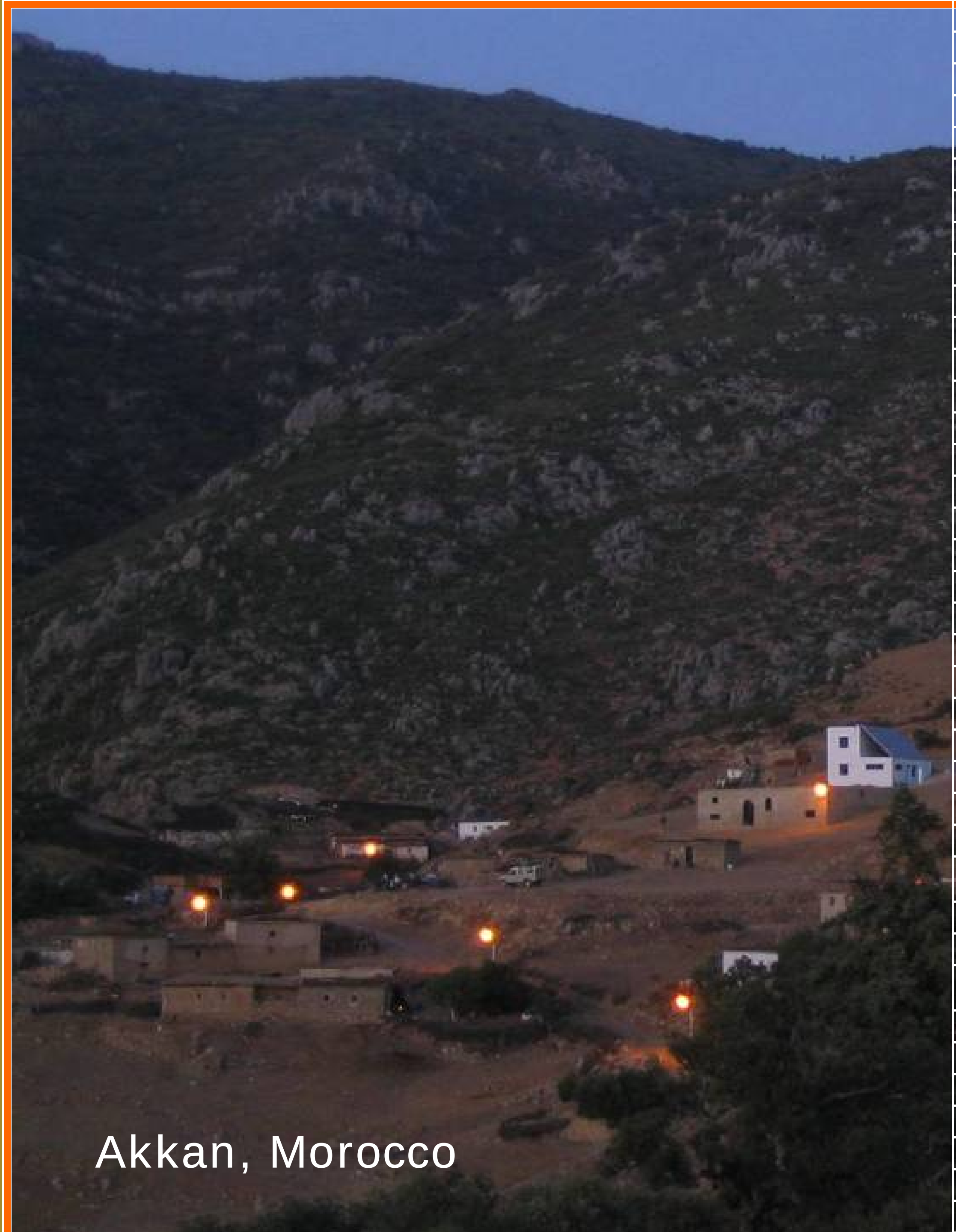

G
G
CONTROL

Demonstration projects from different developing countries on the implementation of rural RE micro grids

- **MSG in Morocco**
- **MSG Senegal**
- **MSG in Cabo Verde**
- **MSG in Palestine (DVD documentary)**

Examples MSG (Multi user Solar Grids)

Akkan, Morocco, Africa



Akkan, Morocco

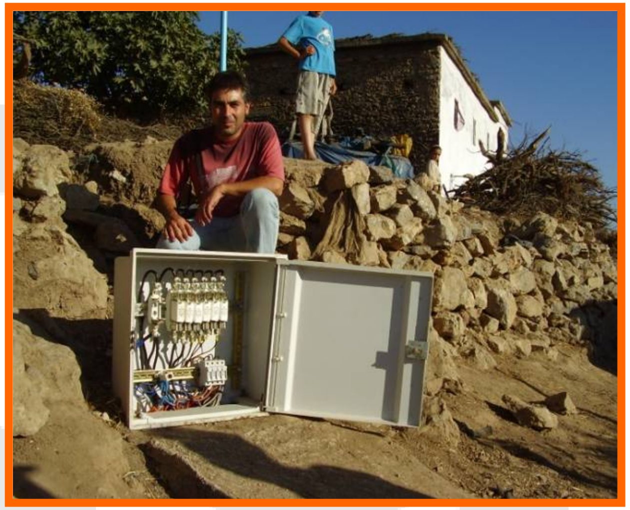
PV HYBRID POWER PLANT	
PV GENERATOR	
Installed PV capacity	5.760 Wp
Module type	80 Wp 36 cell – mono crystalline
Number of modules	72
Inclination / orientation	43º / +5º S
PV CHARGE CONTROLLER	
Rated power	6.000 Wp
Control algorithm	MPPT - Boost
BACK UP GENSET	
Rated power	8,2 kVA single phase
Fuel	Diesel
BATTERY	
Number of elements (voltage)	24 (48V)
Model	Hawker 2AT1500
Capacity (C100)	1.500 Ah
Autonomy	4 days
INVERTER	
Voltage input / output	48 V DC / 230 V AC
Rated power	7.200 W
Harmonic distortion	< 2,5%
DATA LOGGER	
Memory / log frequency	300 kbyte / hourly
Type of data	Energy, voltage, radiation, etc.
ELECTRICITY DISPENSER – METER	
Input	230 V AC 50 Hz
Maximum current	10 A
Algorithm	Configurable Daily Energy Deliverability
STREET LIGHTING	
Number of lamps	13
Type	70 W hp sodium / 2 level electronic ballast
Total power - high	910 W
Total power - low	683 W
INDIVIDUAL LOADS	
Households 275 Wh/day	23
Households 550 Wh/day	3
School 550 Wh/day	1
Mosque 550 Wh/day	1

Technological Configuration – Multiuse building ("Casa de la Luz")

Technological Configuration – single phase LV distribution grid

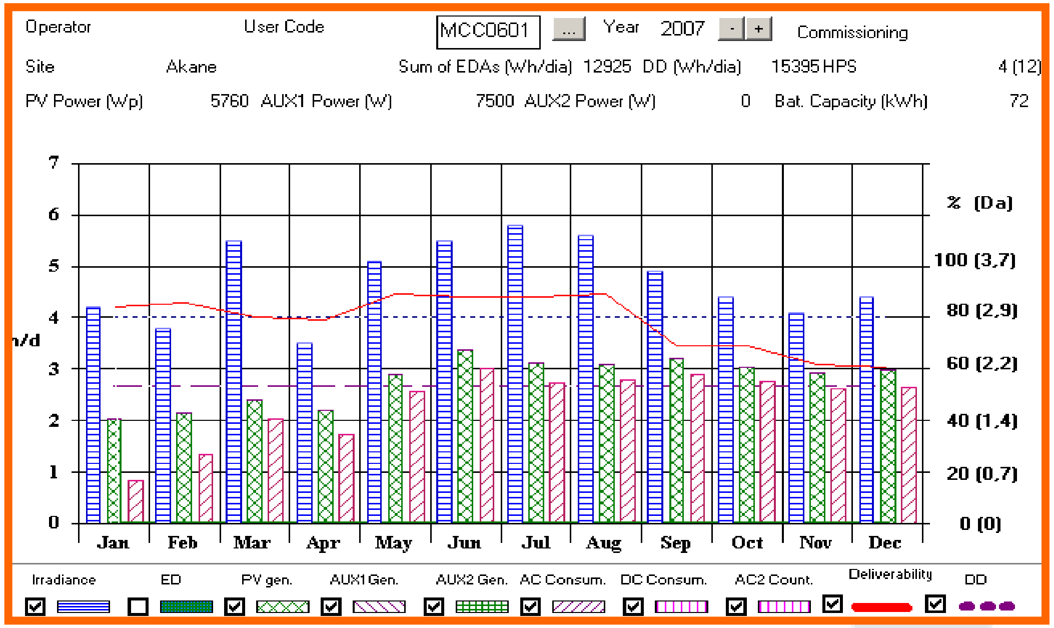


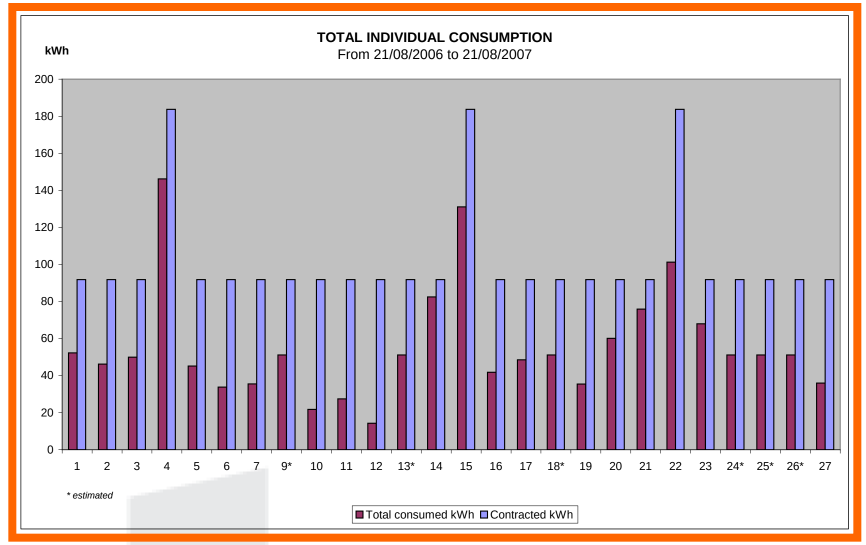


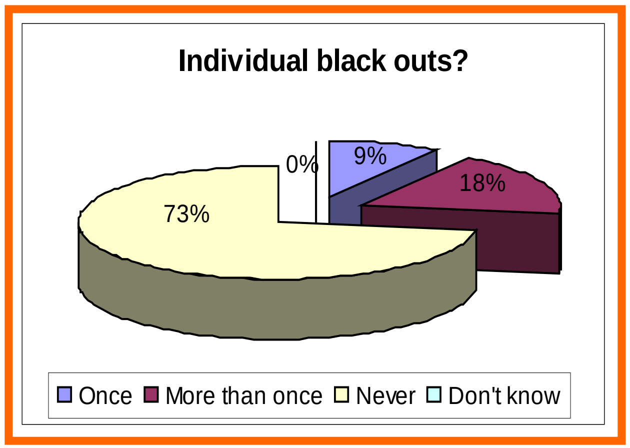



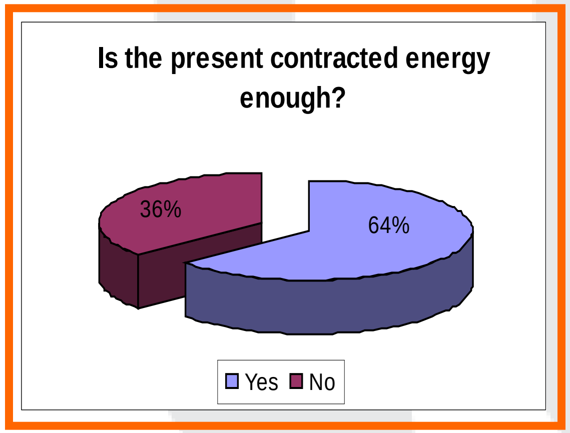
Performance assessment after 1 year

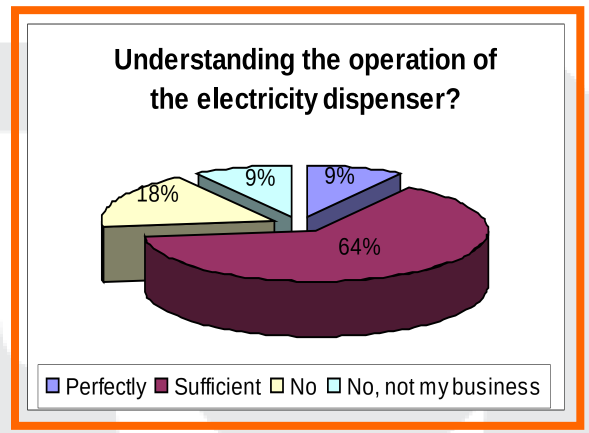
Performance assessment after 1 year



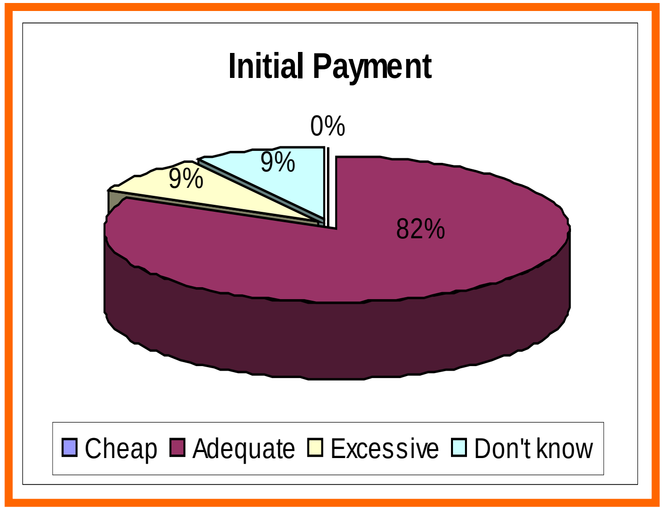


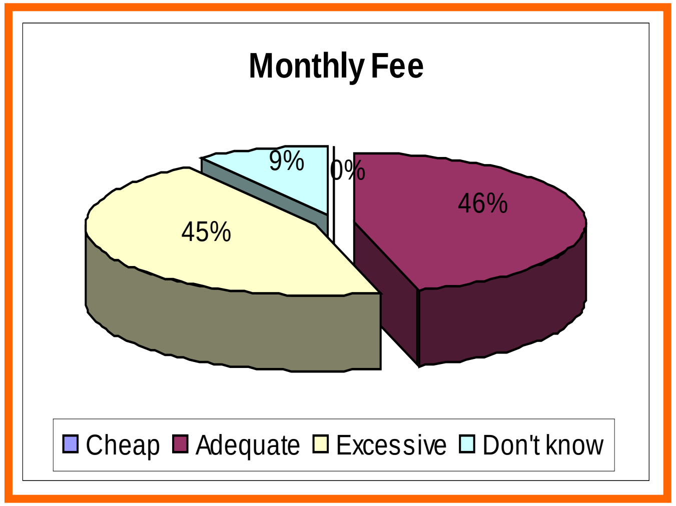


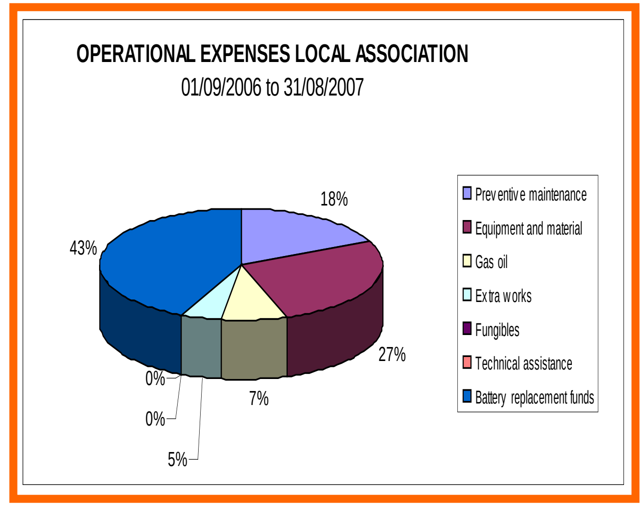


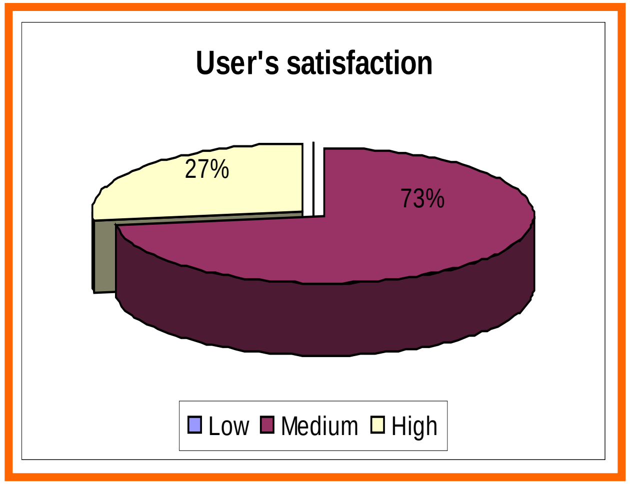


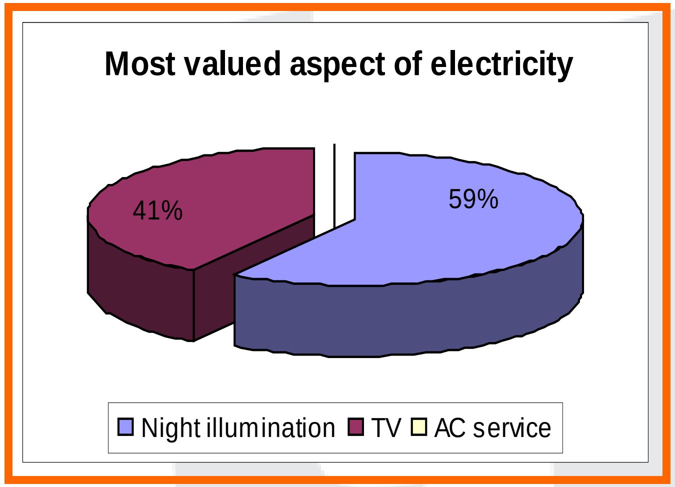
Economical and social

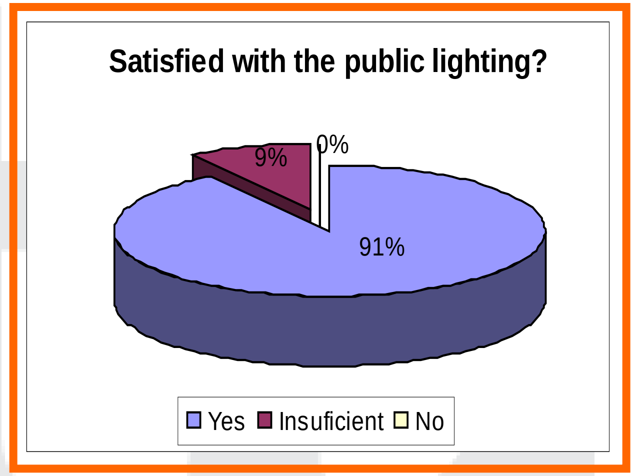




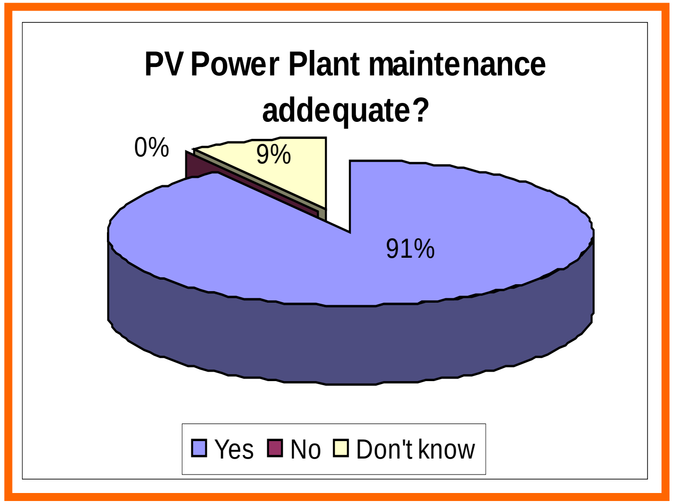


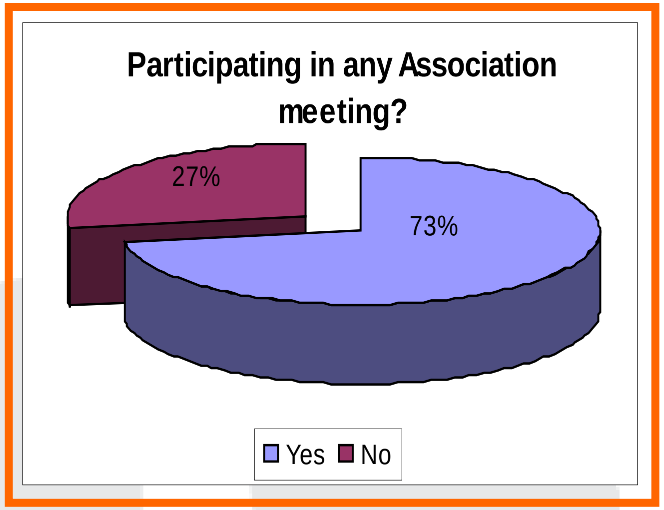




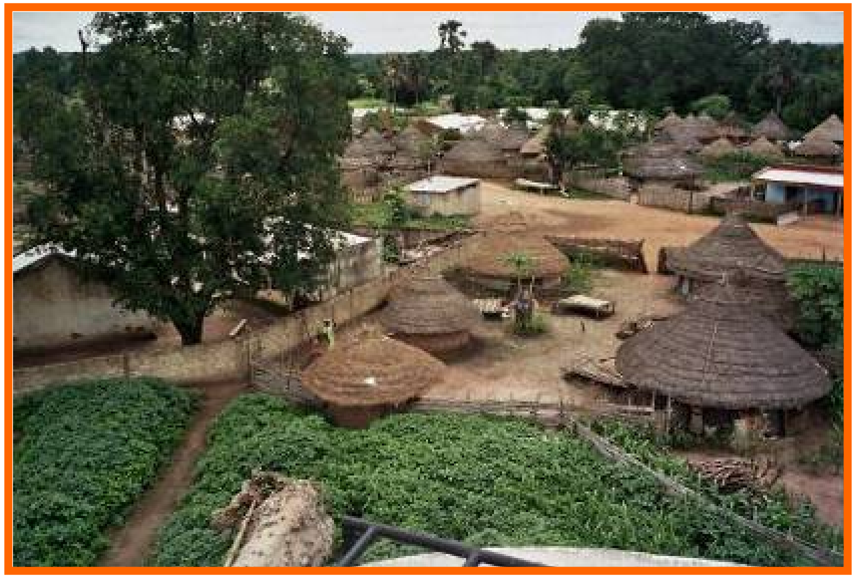


Organizational and institutional





Examples MSG (Multi user Solar Grids)



Diakha Madina, Senegal

Diakha Madina, Senegal

PV GENERATOR	
PV installed capacity	3.150 Wp
PV Module model	PW750 75 Wp 12V
Nº PV modules	42
Orientation/Inclination	0º S / 10º S
PV Area	46 m^2
ENERGY	
Rated Energy Output (Wh/day)	4.803
Irradiation (ḠpHp)	5 HPS
Month of design	December
BATTERY	
Nº cells	24
Battery type	Tudor 6 OPzS 420
Capacity (C100)	672 Ah
Autonomy	4 days
CHARGE CONTROLLER	
Regulation capacity	4.000 Wp
Mode of charge control	MPP Tracker
INVERTER	
Input / Output voltage	48 V DC / 230 V AC
Nominal Power	3.600 W
DC/DC Converter (12 V)	10A máxima de corriente
Harmonic distorsion	< 2,5%
PUBLIC LIGHTING	
Number	2
Type of lamp	70 W / electronic ballast
WATER PUMP	
Power of the pump	1.100 W
Flow	5m^3/h
Depth	49 m
Height of the tank	7 m
Tank capacity	20 m^3
BACK-UP GENSET	
Nominal power	4.2 kW single phase

Examples MSG (Multi user Solar Grids)

Monte Trigo, Cape Verde Africa

- Co financed by the EC under the “ACP-EU Energy Facility”
- 2 local partners: APP, CMPN
- 3 international partners: TTA (E), IDMEC-IST (P), Transenergie (F)

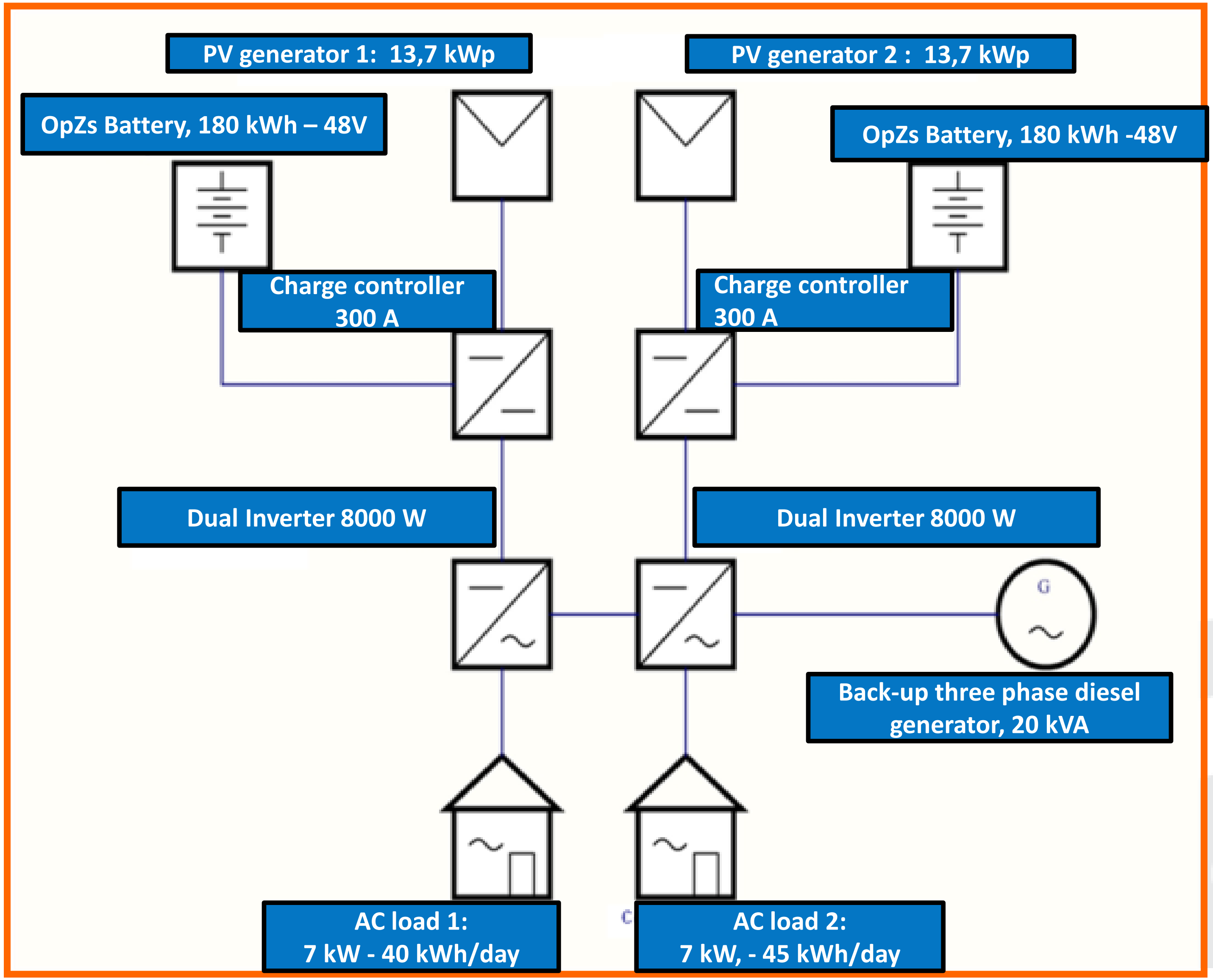
Site: Monte Trigo, 17º01’N , 25º19’O , 00 m s.l.

Monte Trigo: the village

- One hour by boat from nearest village
- 600 people aprox., fishing is main income generating activity
- 80 houses (60 connected), school, medical centre, kindergarten
- hostel for visitors, several small shops, connection for telecommunications and TV
- Deferrable load: ice making
- PV electricity since February 2012

Monte Trigo electrical diagram

AC linked double DC bus configuration



ESQUEMA DISTRIBUÇÃO LINHAS ELÉCTRICAS PROPOSTAS

CARACTERÍSTICAS DISTRIBUÇÃO DE LINHAS:

As linhas de distribução das conexões a rede e iluminação pública decorrerão aéreas.

O cabeamento instalado estará protegido contra a corrosão e terá resistência mecânica suficiente.

Não se prevê a construção de novas linhas de distribução.

LEGENDA	
●	Poste de madeira para tendido eléctrico
C	Poste de lux com lâmpadas 70W
P	Poste metálico embutido na parede
P/C	Poste embutido na parede com lâmpada 70W
——	Linha aérea 3x25+16mm2
——	Linha aérea 4x16 mm2
	NOVAS ACTUAÇÕES
——	Linha enterrada tubulação 4x25mm2
——	Linha superficial tubulação 4x25mm2
——	Linha aérea, Substituir 4x16mm2 por 4x25mm2
——	Linha aérea, 4x16mm2 a estender (cabo reutilizado e novo)

Escala: 1/200

Serviço de energia sustentável para as aldeias rurais isoladas mediante microredes com energias renováveis na Ilha de Santo Antão

Nome:

PROJETO SESAM-ER (Monte Trigo, Cabo Verde)

PROPOSTA DISTRIBUÇÃO LINHAS ELÉCTRICAS

Socios promotores:	Financiado por:	El Ingeniero Industrial	Escala: 1:200
sesam-er	EUROPEAN COMMISSION	Xavier Vallvé	Nº Plano: 05–04

RURAL RE MICROGRID (kWh/day	
PV GENERATOR	
Installed PV capacity	27 300 Wp
Module type	130 Wp 36 cell – mono crystalline
Number of modules	210
Inclination / orientation	15º / +20º S
PV CHARGE CONTROLLER	
Rated power	2x12 000 Wp
Control algorithm	MPPT - Boost
BACK UP GENSET	
Rated power	20 kVA 3- phaseS
Fuel	Diesel
BATTERY	
Number of elements (voltage)	24 (48V)X2
Type	Lead acid OPzS tubular
Capacity (C100)	3 850 Ah – 370 kWh
Autonomy	4 days
INVERTER	
Voltage input / output	48 V DC / 230 V AC
Rated power	7 000 W
Harmonic distortion	< 2,5%
DATA LOGGER	
Memory / log frequency	300 kbyte / hourly
Type of data	Energy, voltage, radiation, etc.
ELECTRICITY DISPENSER – METER	
Input	230 V AC 50 Hz
Maximum current	Configurable
Algorithm	Configurable Energy Daily Allowance
DISTRIBUTION LINE AND STREET LIGHTING	
Line Length	800m
Number of lamps	20
Type	70 W hp Na / 2 level electronic ballast
INDIVIDUAL LOADS	
Households 825 Wh/day	20
Households 1100 Wh/day	18
Households 1650 Wh/day	14
Households 2200 Wh/day	6
School 1650 Wh/day	1
Ice machine 4200 Wh/day	1

Organization Model: Government owner-Private Operator

Organization Model scheme Monte Trigo	
Role	**Responsible**
MSG Owner	Local Municipality: "Camara Municipal Porto Novo"
Tariff collection	Private Firm: "Aguas de Porta Preta (APP)” on behalf of Municipality
Electricity Service Operator	Private Firm: "Aguas de Porta Preta (APP)"
MSG Technical Operation and Maintenance	Private Firm: "Aguas de Porta Preta (APP)"
MSG Basic Operation and up keeping	2 trained caretakers, chosen among local users´ community

Monte Trigo energy demand segmentation

Total Aggregate Demand (EDA tot) = ∑ EDAi = 90kWh/day
Utilization Factor (Uf) : 0,80
Future Demand Forecast (Di): 20%

Design Demand (DD): EDA tot * Uf * (1 + Di) = 85 kWh/day

	Domestic "very low"	Domestic "low"	Domestic "medium" and community buildings	Domestic "high"	Shops	Ice maker machine	Public lighting
Type	•Low power devices • Low and rigid demand profile	• Low power devices • Refrigerators • Low demand profile	•Like previous type but higher number of hours usage	•Higher power devices • Refrigerators • Iron • Variable profile	•High power devices • Refrigerators • Iron • Frezer • PC •Variable profile	•1000W machines for ice making (2 units)	•Public lighting •20 lights– 70W sodium • two power level programmable
Maximum Power	*P* ≤550 W	*P* ≤550 W	*P* ≤1000 W	*P* ≤1500 W	*P* ≤ 1500 W	*P* ≤ 1500 W	683W ≤ P <1400W
EDA (Energy Daily Allowance)	*E* ≤ 825 Wh	*E* ≤ 1100 Wh	*E* ≤ 1650 Wh	*E* ≤ 2200 Wh	*E* ≤ 3300 Wh	*E* ≤ 4400 Wh	E <5000 Wh

Tariffs and financial sustainability

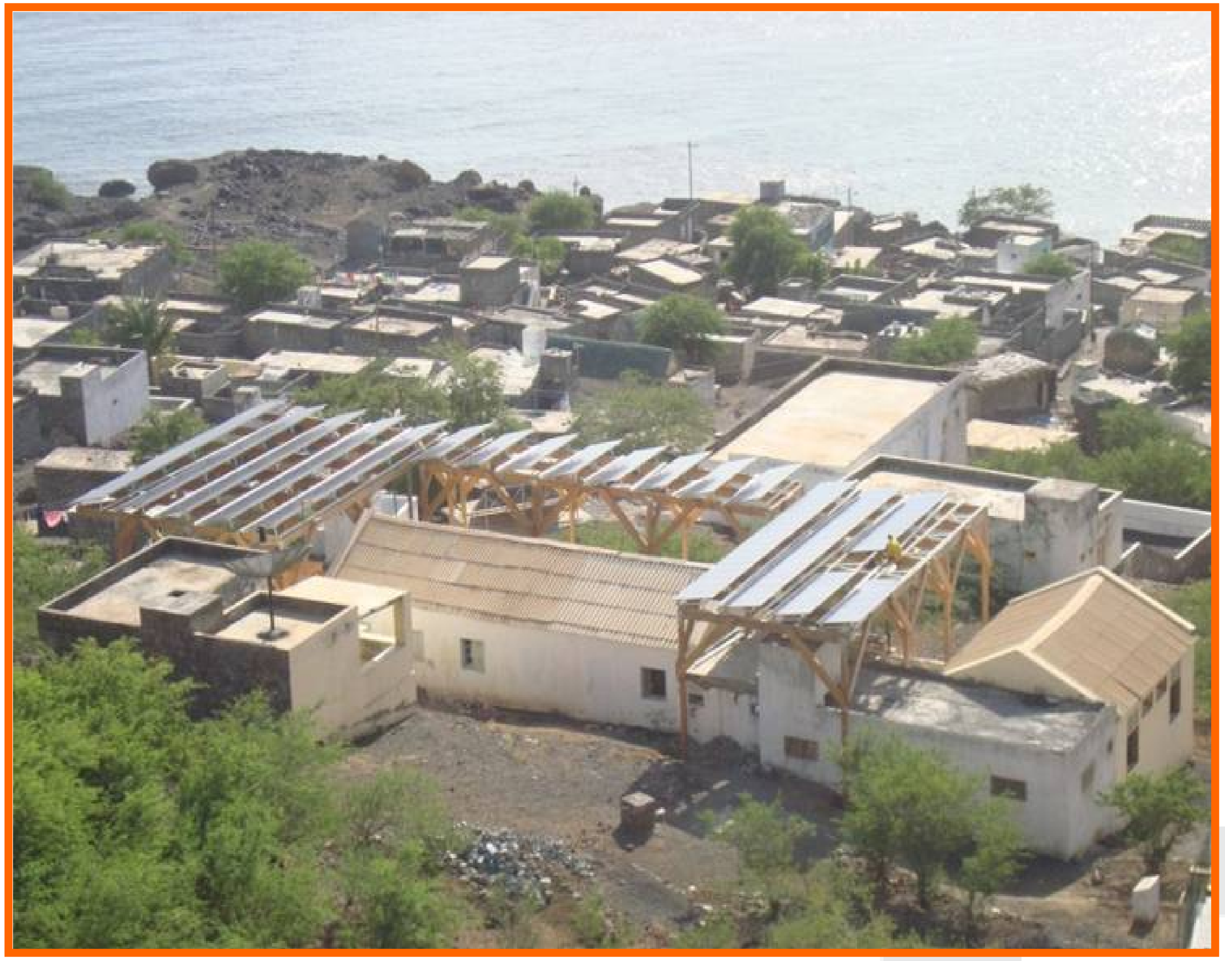
Compromise between users' willingness to pay and economic sustainability

Flat monthly tariff according to EDA level, power limit and virtual energy storage

Financial Sustainability	
Initial investment	75% UE, 25% project partners (private, public)
Tariff scheme	Flat monthly fee based on EDA concept
Fee decision	Ongoing discussion with National Regulator

Category	EDA (Wh)	Power Limit (kW)	Max. Energy storage cpacity (EDA)	Adopted monthly fees (Eur)	Proposed monthly fees (Eur)
T0301	825	0,55	6	8,51	11,52
T0401	1100	0,55	6	10,85	14,58
T0602	1650	1,1	6	15,84	21,12
T0802	2200	1,1	6	20,81	27,64
T1203	3300	1,65	6	30,47	40,30

Added value solution: PV pergola

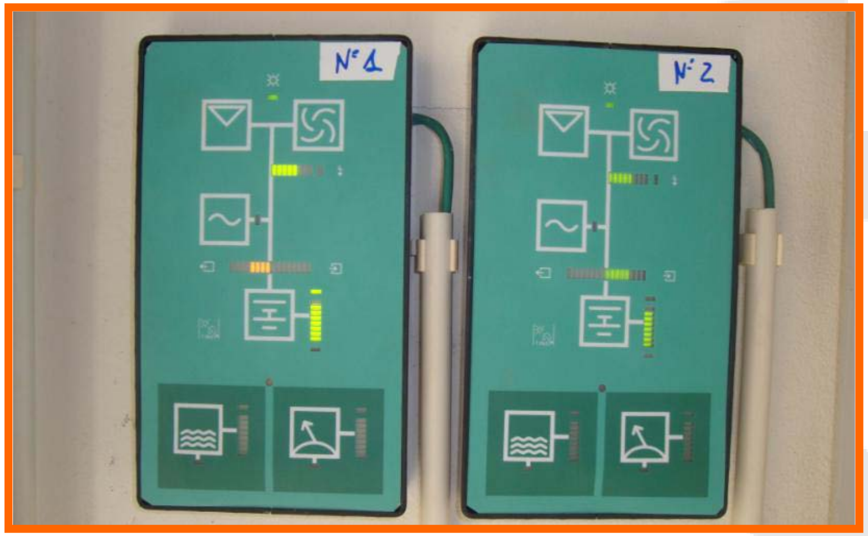


Added value solution: Engage the users

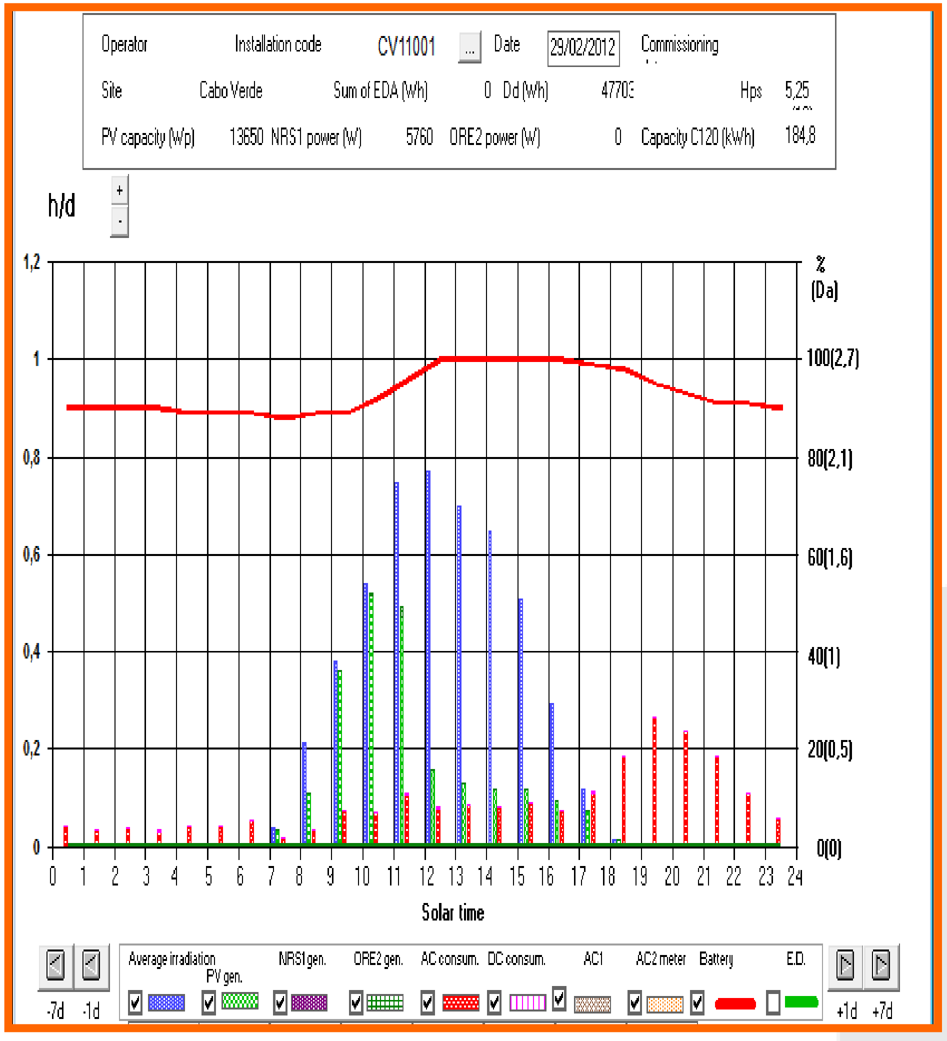
Technical solution: mechanical room

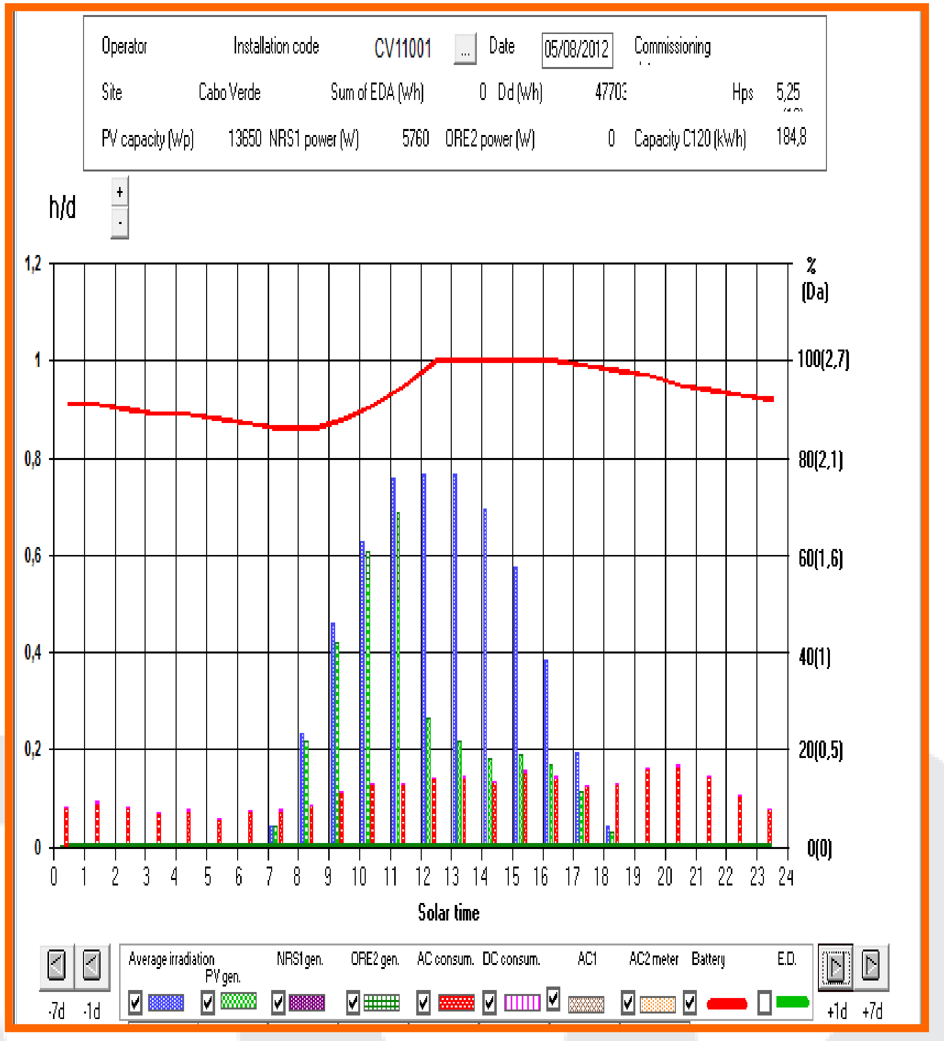
Technical solution – Single phase LV distribution

Technical solution – User interface



Effects of Dispenser's signal on consumer habits

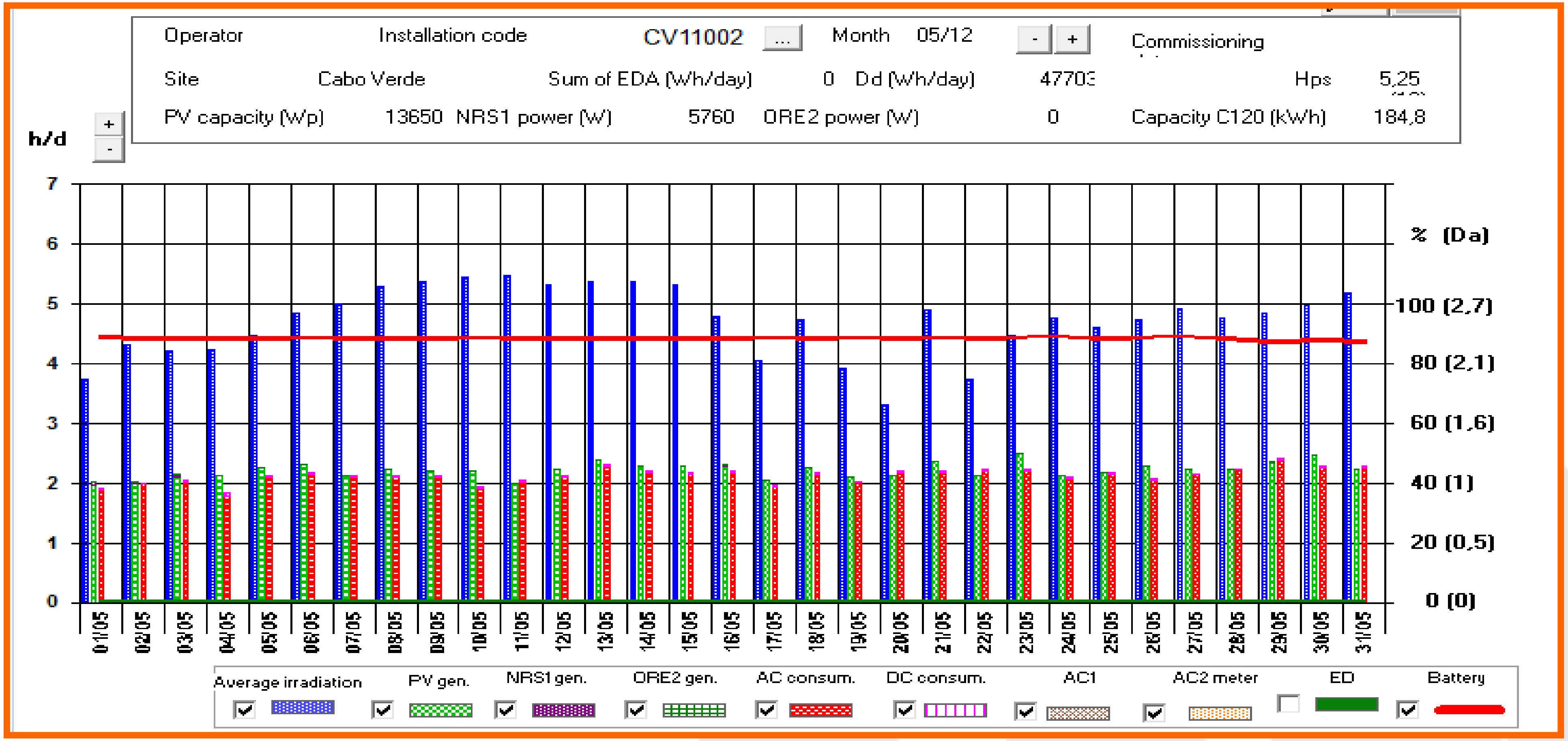




Normalized Performance indicators

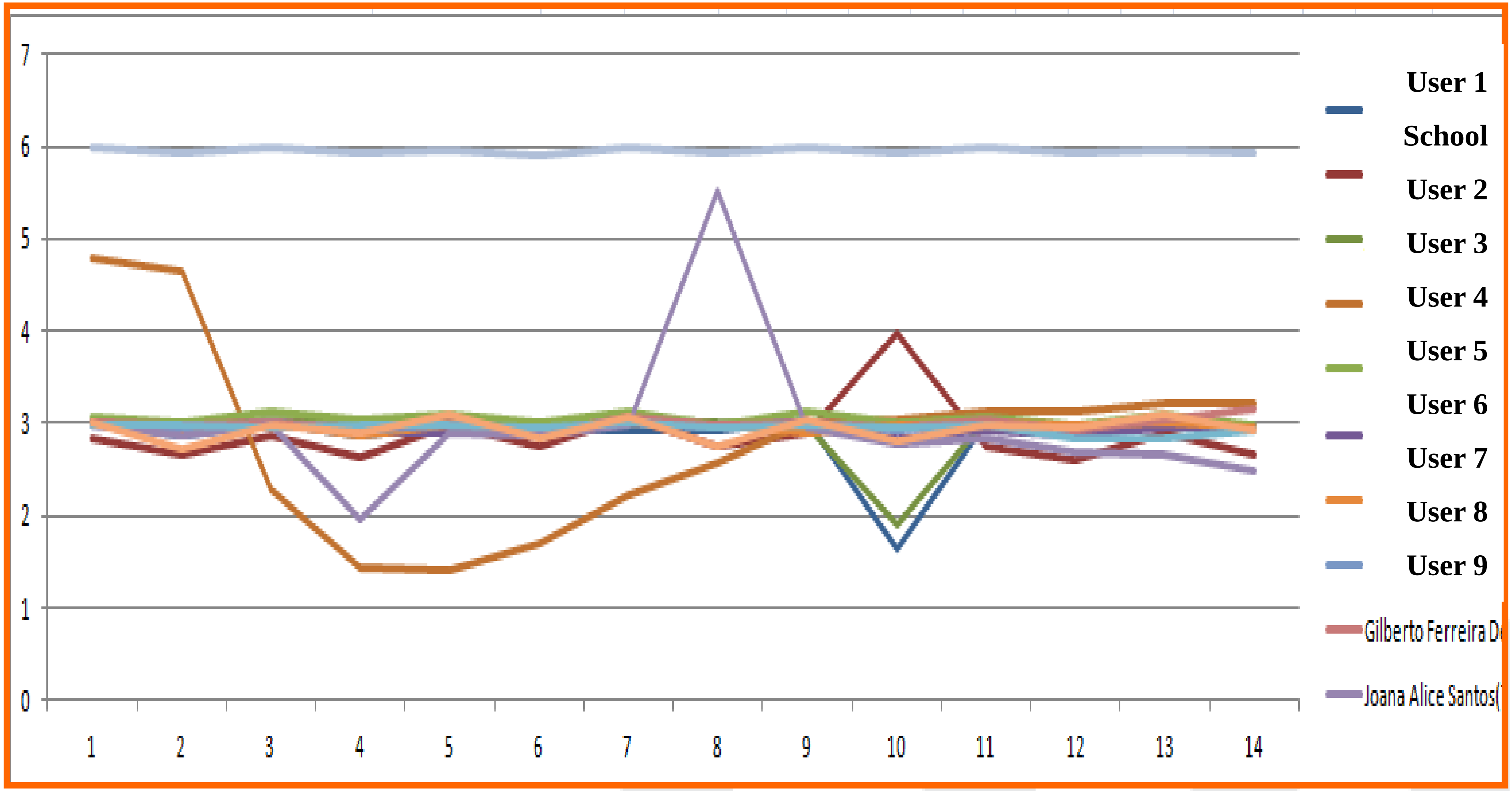
Stable daily aggregate load (red bars)

Battery state of Charge (red line) always between 85% and 95%



User Behaviour

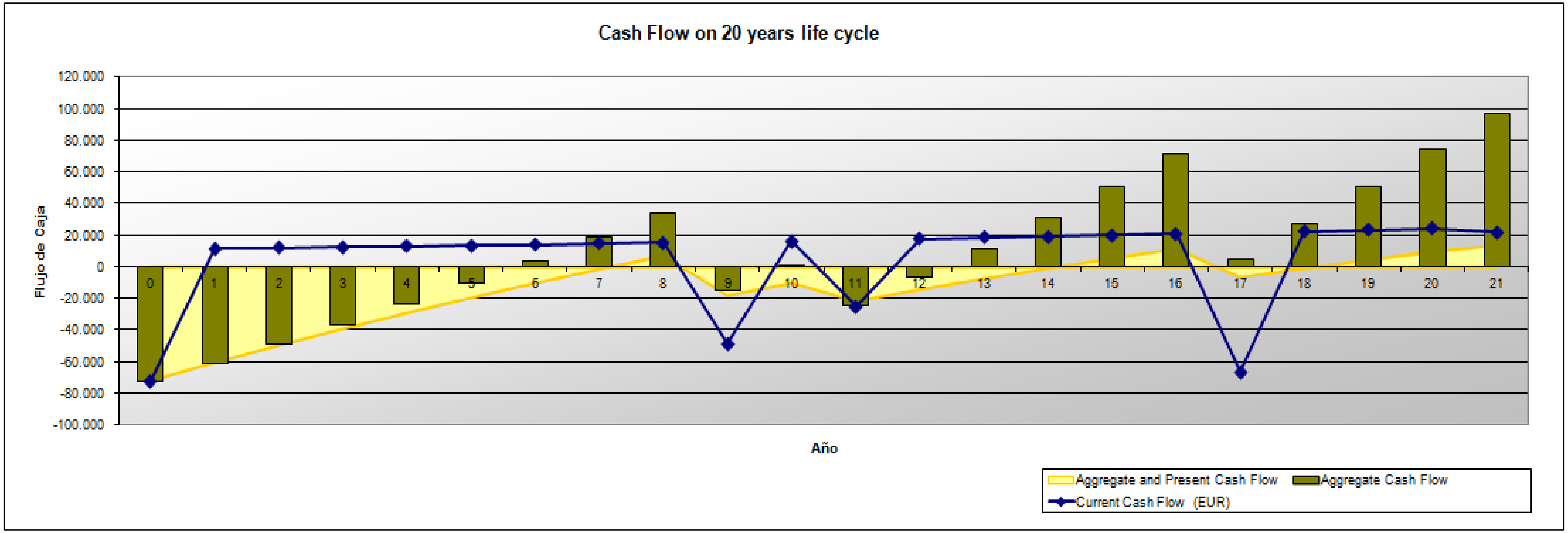
Reading of remaining energy for 10 users confirms the optimized utilization by the users



EDA max available: 6*EDA/day

Economic analysis: recommended tariffs

Discount Rate	8,5%
Initial investment to recover	25%

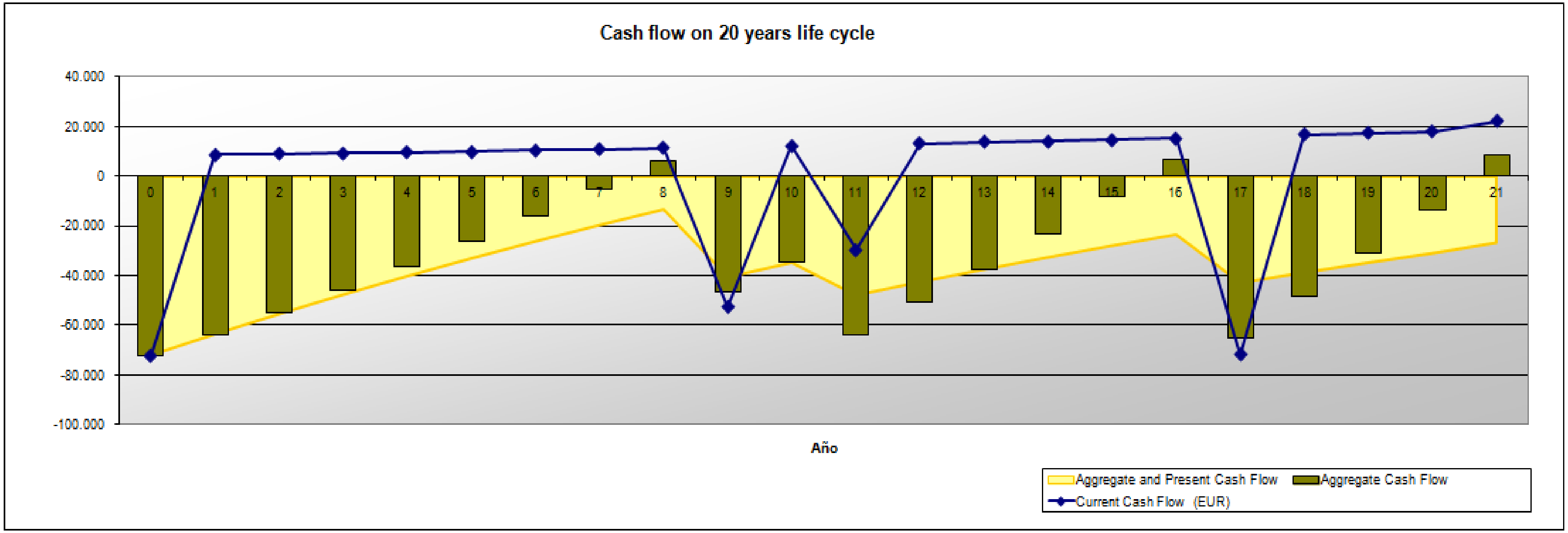


NPV 13.871 EUR **Sustainable Project**

Economic analysis: probably adopted tariffs

Discount Rate 8,5%

Initial investment to recover 25%



NPV -26.771 EUR NON Sustainable Project

Thanks for your attention!

xavier.vallve@tta.com.es