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DESIGN CRITERIA FOR SOLAR PV RURAL MICRO GRIDS FOR VILLAGE ELECTRIFICATION

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Trama TecnoAmbiental (TTA)

- SME Founded in Barcelona en 1986
- Independent Consultants in distributed Renewable Energy
- Consultancy, engineering, research, project management, social aspects, financial, …
- Since 1988: 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 RE micro plants Southern Europe

Catalonia and Balearic Islands, Spain (1988)

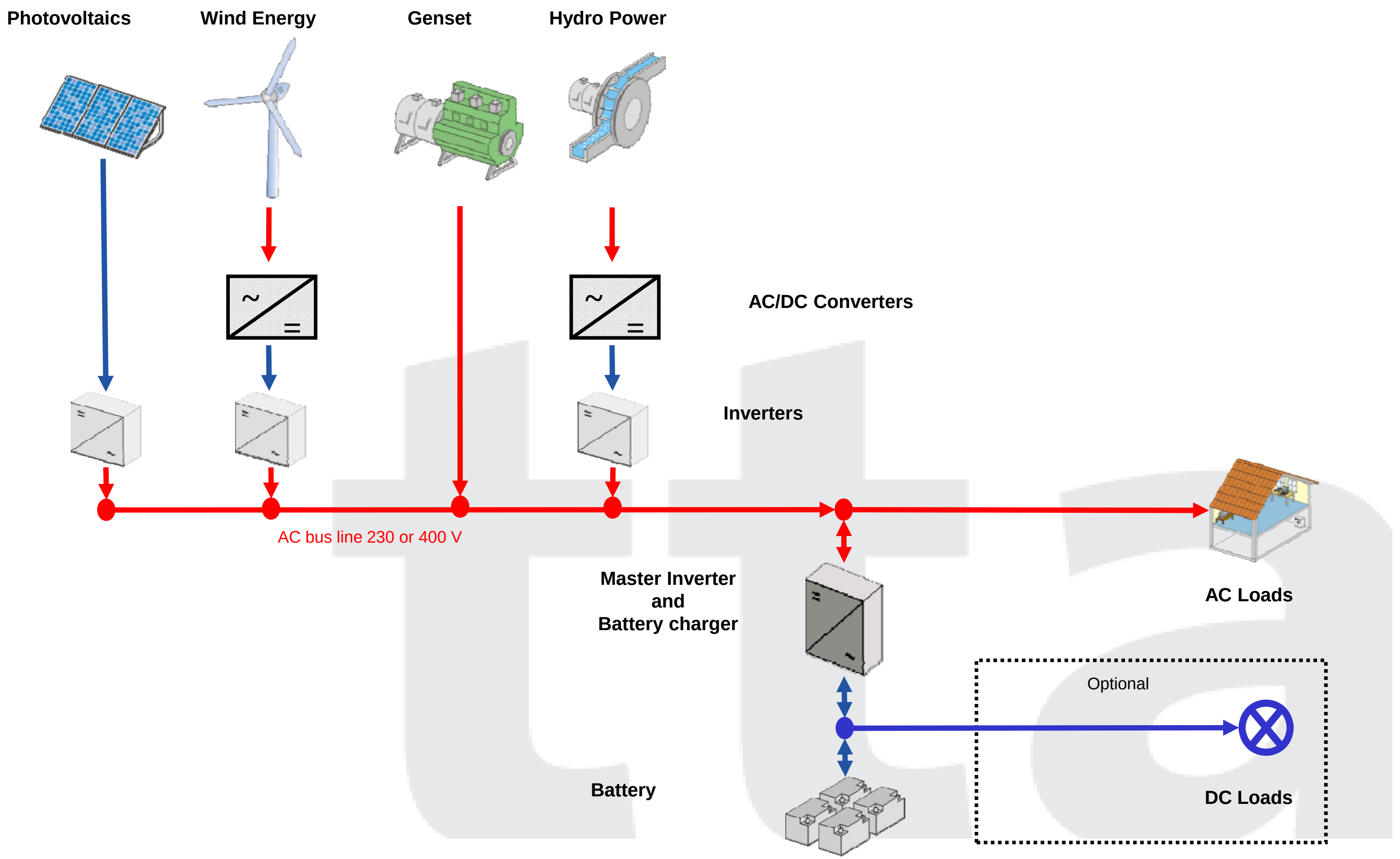
Structure of Hybrid Micro power plants-AC coupling

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.

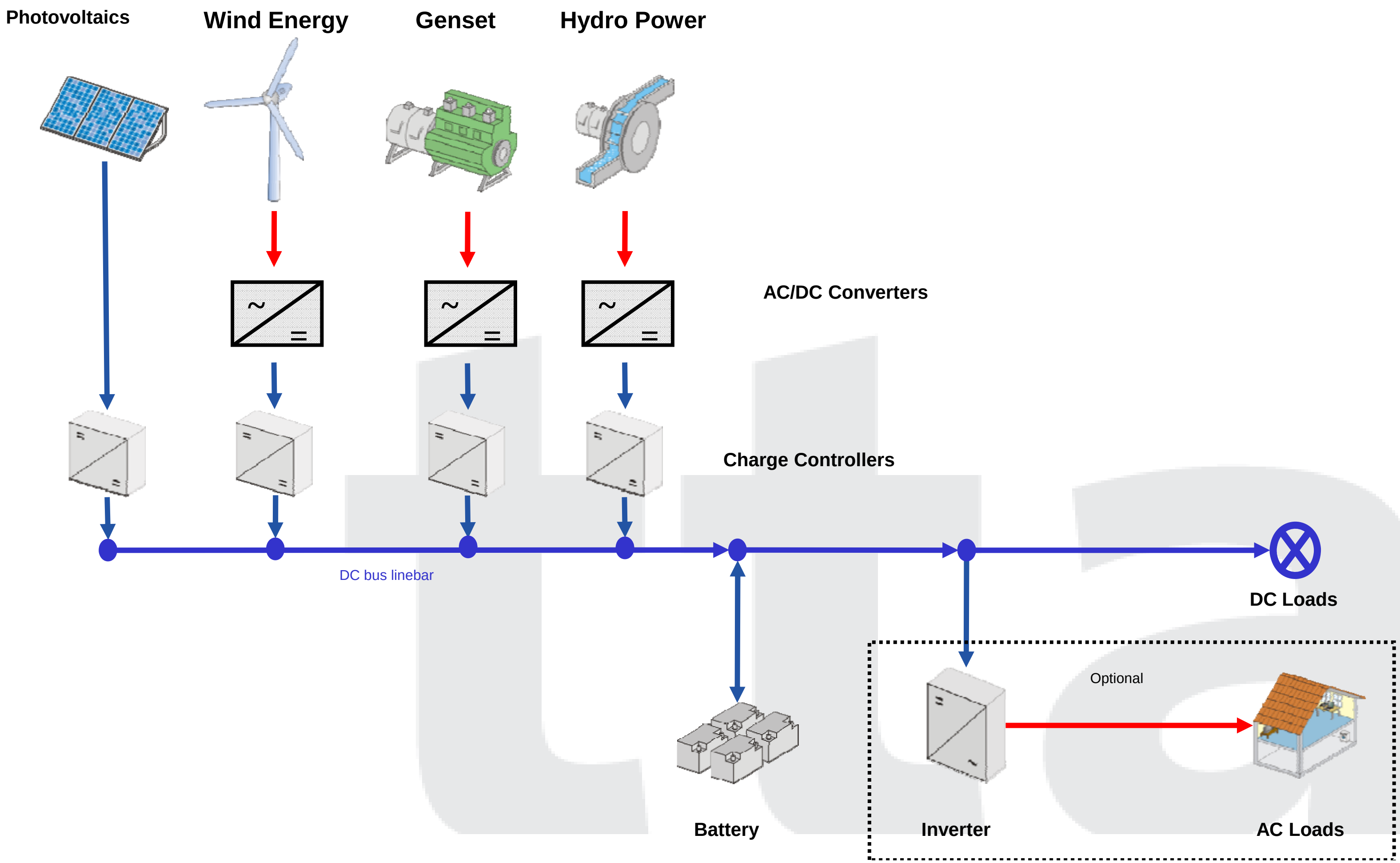


Structure of Hybrid Micro power plants-DC coupling

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.



From individual PV hybrid autonomous power plants (AC, DC or combined coupling) 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

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

- Electricity generation based on renewable energies or mixed (RE + genset)
- Steady village-level electricity service, offering also the possibility to be upgraded to either more capacity, clustering or interconnection
- Installed capacity up to 100 kW (according to IEC)
- Distribution line in Low Voltage
- Single or 3-phase grid
- Operational scheme

PV Hybrid Micro Grid in West Bank, Palestine

Pioneer PV rural micro grid

Andalucía, Spain (1994)

STATE OF THE ART: Typical Design approach

- Demand analysis, segmentation and load management is a key issue
- Technical solutions with high RE penetration (>70%) are a challenge because the intermittence of energy generation
- Renewable Energy multi source micro-power plants with electrical configuration DC based, AC based or combined at ELV (extra low voltage)
- Quality of engineering and components to achieve long lifetime and lowest levelized cost (LCOE)
- Technical specifications and best practices from Pilot Projects, IEC technical specifications, IEA PVPS Task3 and Task11 recommended practices, etc
- Sinusoidal single phase LV distribution
- Design of **metering** concept and **demand management** impacts on **business model**

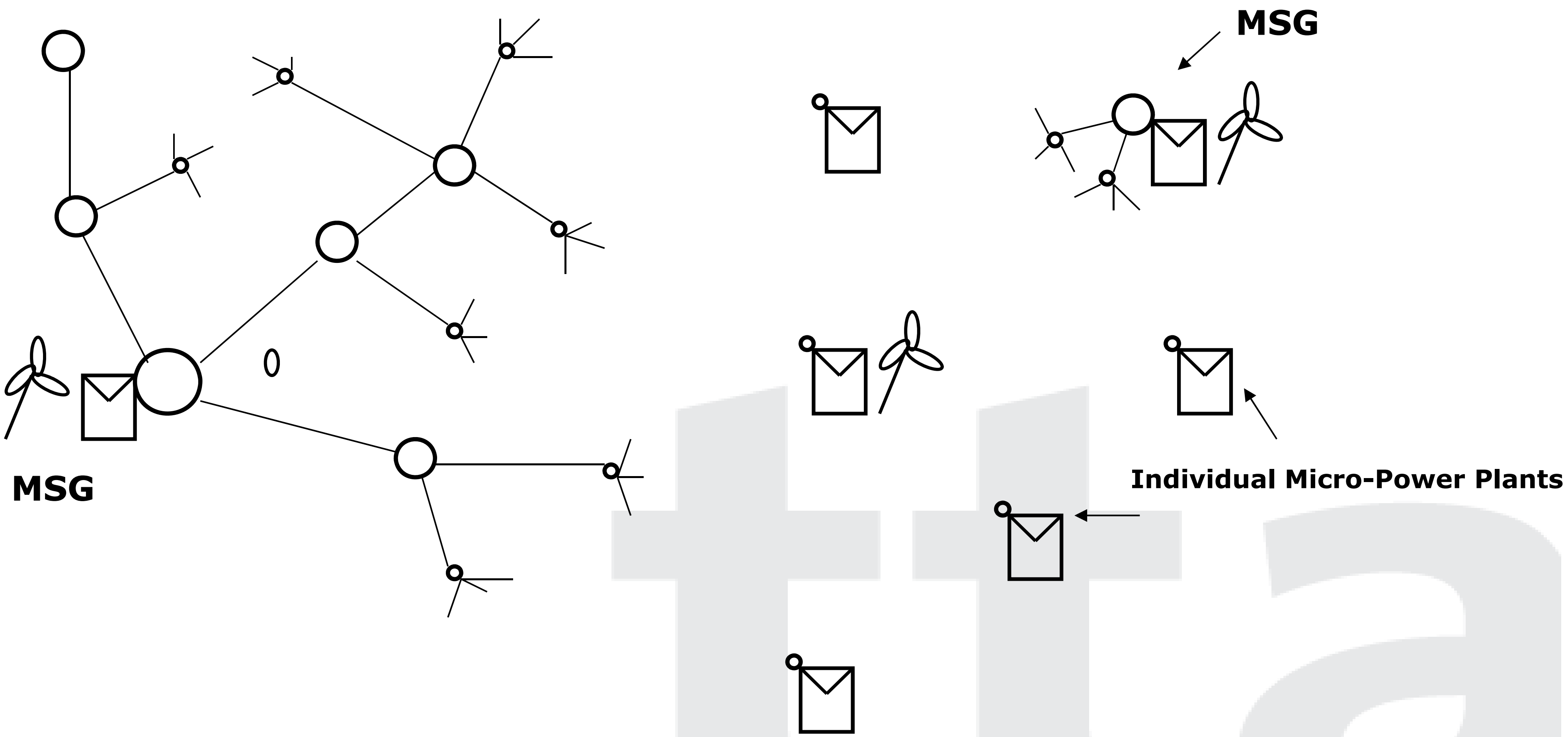
Comparison of PV Individual and Micro Grids

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 and surge power • Efficient and cheaper maintenance • Easily expandable • Lower investment for compact villages. • Telemetry can be economic for monitoring plant's status.	• Shortages 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**

➔ **Need innovative approach to energy distribution and metering!**

VISION: Universal electrification-individual plants and micro grids under one invoicing concept



Load related challenges in rural micro grids

- **Social Aspects:**
  - to identify the different energy needs (basic, productive, deferrable, etc) and to ensure a resource distribution without conflicts

- **Individual energy demand management :**
  - to encourage the consumption during surplus RE generation periods
  - to manage each user's energy in an independent and flexible way
  - to guide users' energy consuming habits to optimize energy management

- **Techno-economic long term sustainability:**
  - to reduce uncertainty on invoicing and unpaid fees
  - to ensure that batteries, inverters etc. will operate within design range

Innovative concept: 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 because of flat fees

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: 6 x EDA
- Programmable power limitation

Auxiliary Smart switch (5A) :

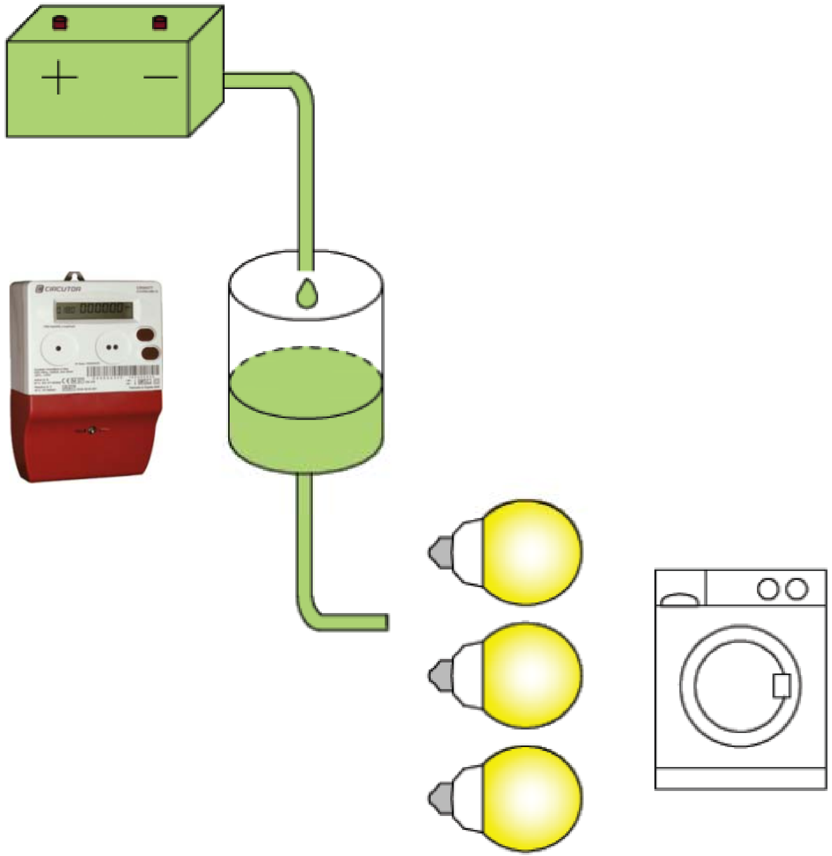
- for deferrable loads

Smart RFID card for:

- Tariff management
- Energy swapping between users
- Invoicing management

- **Certified energy 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 according to real time plant condition

- Demand management in indication according to energy status in PV plant
- Can influence on the consumption in real time by applying a pricing factor

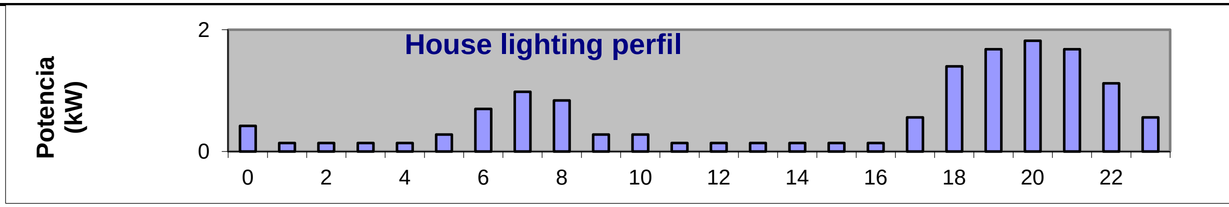
Mode	Description	Factor	Activation
Normal	EDA and power to rated values	1	Energy in the in the microgrid is between normal values
Bonus	Consumed energy price lower than “normal” price	0,5	PV controller is curtailing
Restriction	Consumed energy price higher than “normal” price	2	Battery state of charge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

Assessment of the aggregate demand: example

House lighting =

OK

Total load= 14,00kWh/d



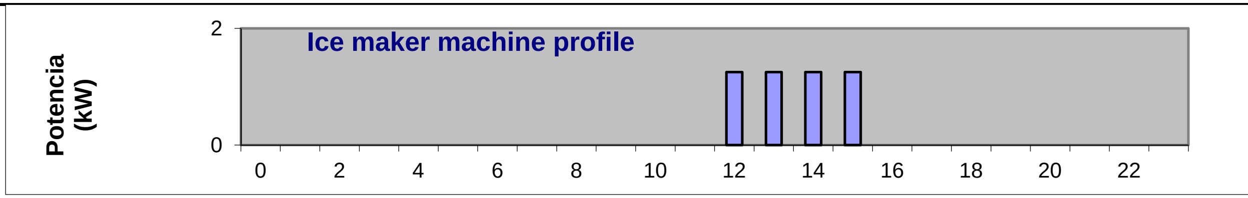
Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Porcentage	3	1	1	1	1	2	5	7	6	2	2	1	1	1	1	1	1	4	10	12	13	12	8	4	100,0%
Power (kW)	0,4	0,1	0,1	0,1	0,1	0,3	0,7	1	0,8	0,3	0,3	0,1	0,1	0,1	0,1	0,1	0,1	0,6	1,4	1,7	1,8	1,7	1,1	0,6	14,00kWh

+

Ice maker machine =

OK

Total consumo= 5,00kWh/d



Hora	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Porcentaje	0	0	0	0	0	0	0	0	0	0	0	0	25	25	25	25	0	0	0	0	0	0	0	0	100,0%
Potencia (kW)	0	0	0	0	0	0	0	0	0	0	0	0	1,3	1,3	1,3	1,3	0	0	0	0	0	0	0	0	5,00kWh

+

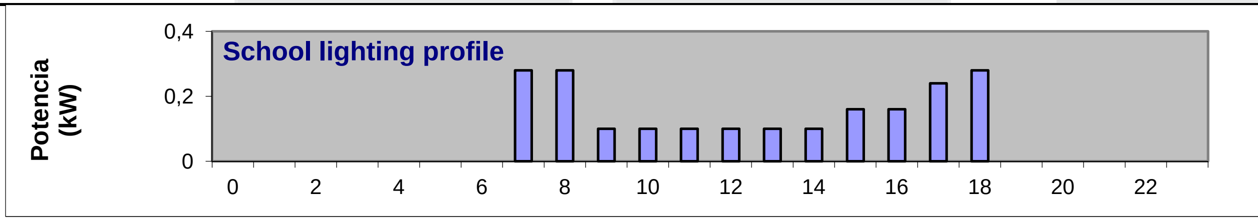
....

+

School lighting =

OK

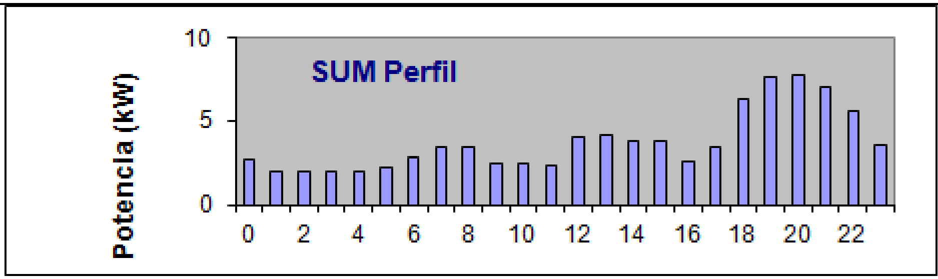
Total load= 2,00kWh/d



Hora	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Porcentaje	0	0	0	0	0	0	0	14	14	5	5	5	5	5	5	8	8	12	14	0	0	0	0	0	100,0%
Potencia (kW)	0	0	0	0	0	0	0	0,3	0,3	0,1	0,1	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,3	0	0	0	0	0	2,00kWh

Simplified PV generator sizing

SUM



Power Peak = 7,8 kW

Total load = 90,0 kWh/d

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Power (kW)	2,7	2	2	2	2	2,3	2,9	3,5	3,5	2,5	2,5	2,3	4	4,2	3,8	3,8	2,6	3,5	6,3	7,7	7,8	7,1	5,6	3,6

$$DD_{total}\ (kWh) = \sum_i DD_i = 90\ kWh$$

$PR = 0,6$ $\quad fu = 0,8$ $\quad h_p = 5,2$ (December)

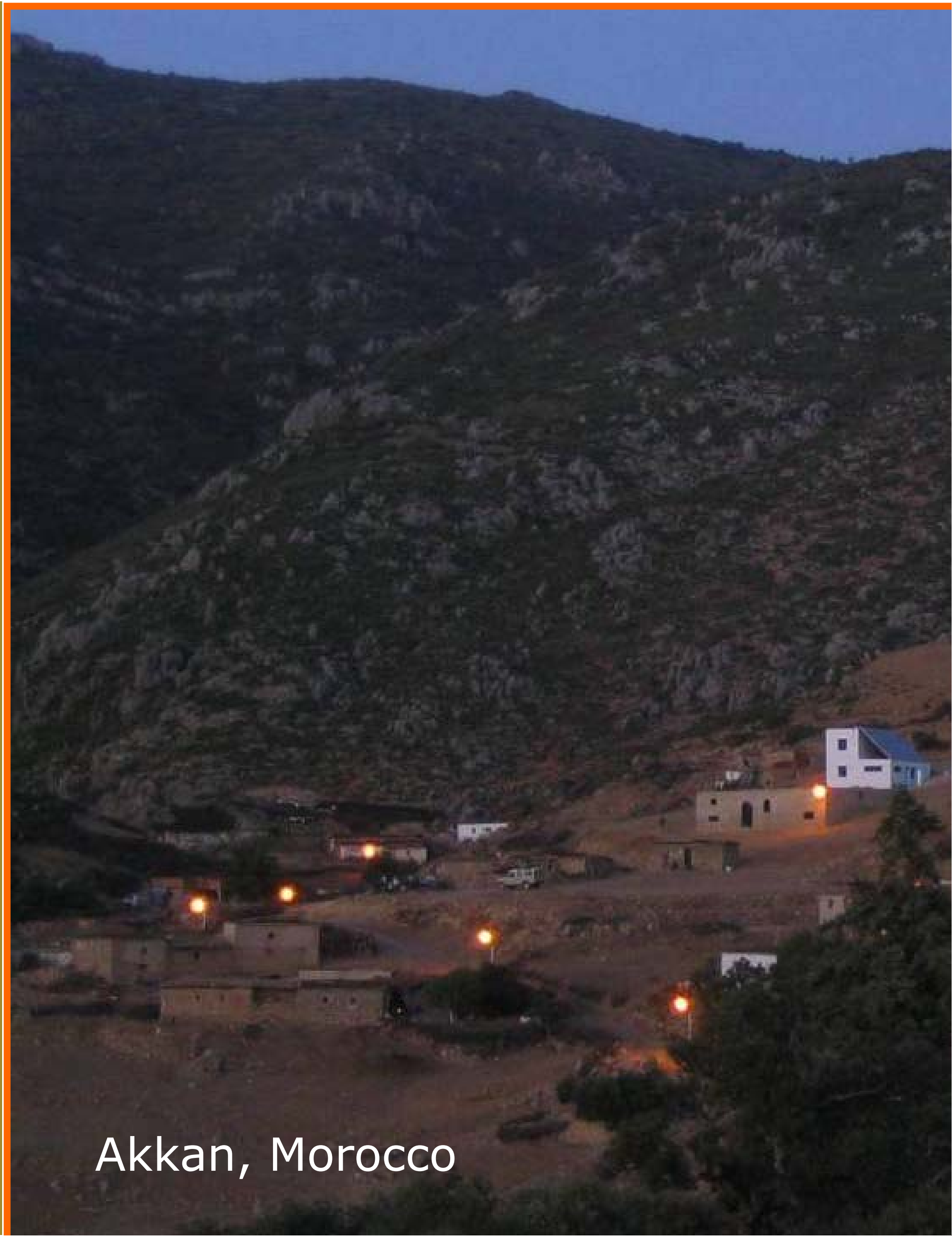
$$P_{FVSTC} = 90 * 0,8 * 1,2 / (0,6 * 5,2) = 27,7\ kWp$$

Case studies of PV micro grids in African countries

- MSG in Morocco
- MSG Senegal
- MSG in Cabo Verde

Example MSG (Multi user Solar Grid)

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")

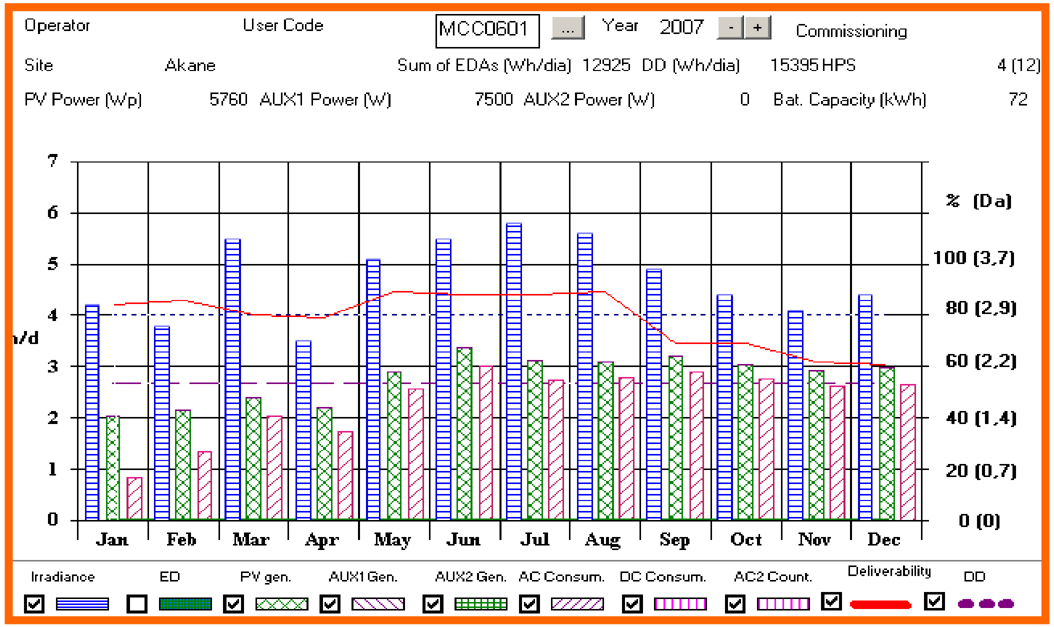
Technological Configuration – single phase LV distribution grid

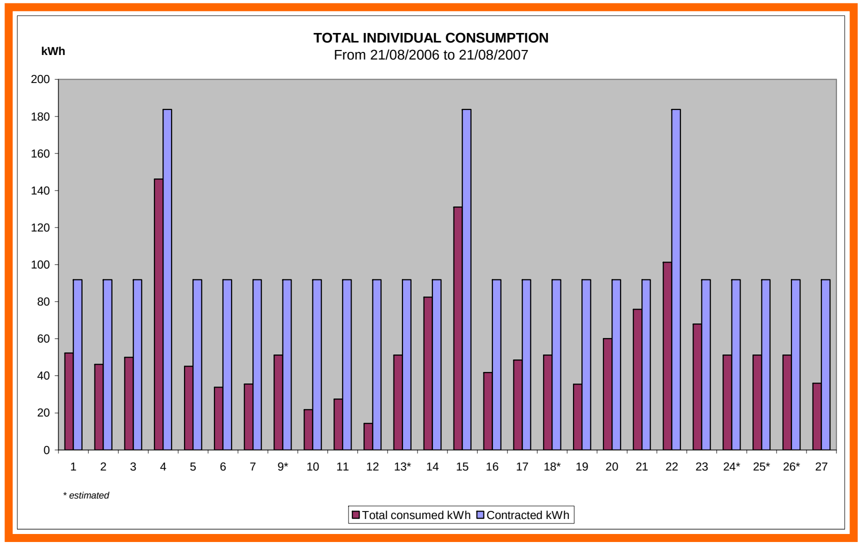


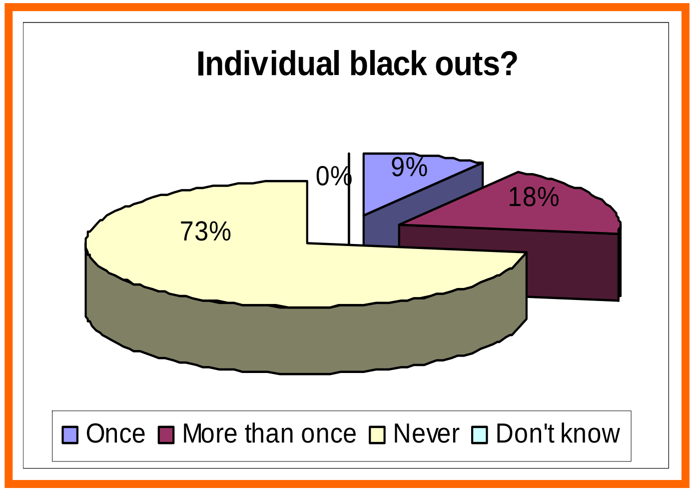


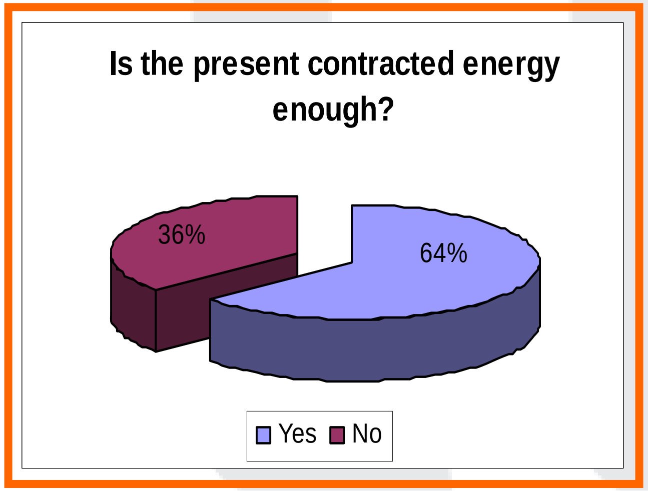

Performance assessment after 1 year

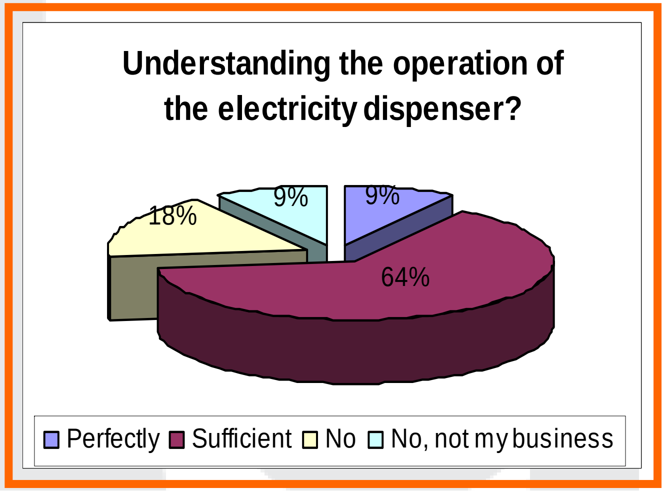
Performance assessment after 1 year



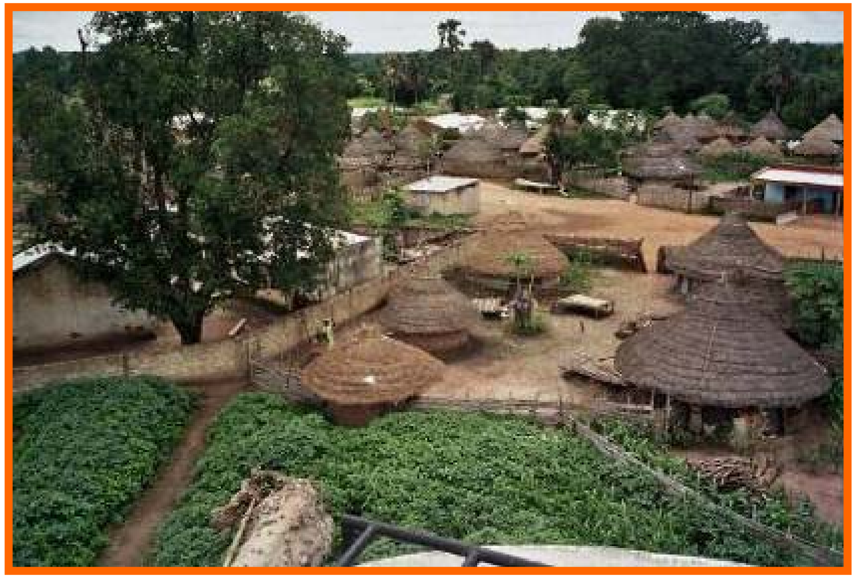








Example MSG



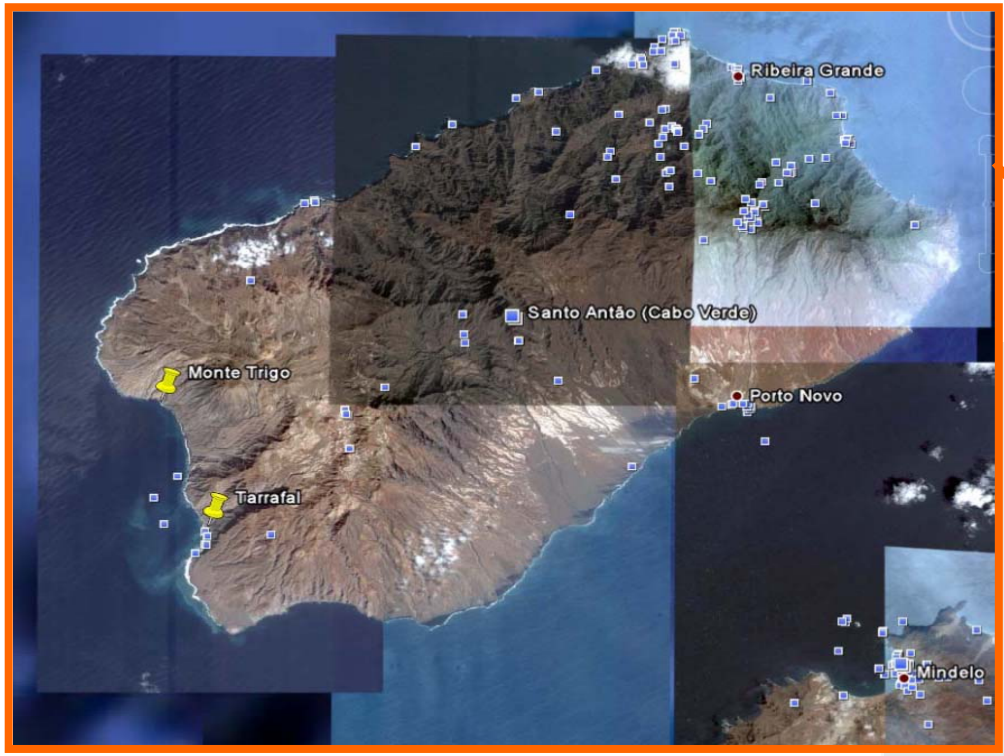
Diakha Madina, Senegal

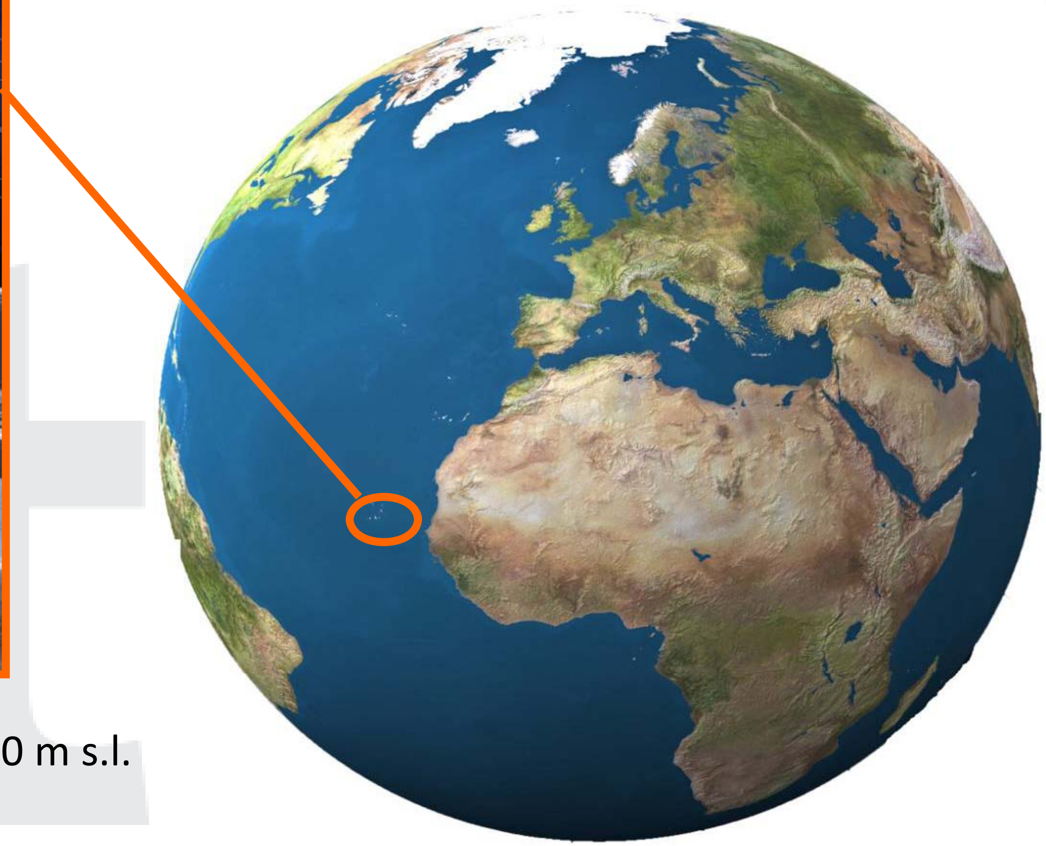
Diakha Madina, Senegal

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
Fuel	Diesel

Example MSG

Monte Trigo, Cape Verde





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

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	2 X 8 000 W
Harmonic distortion	< 2,5%
DATA LOGGER	
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

Monte Trigo energy demand segmentation

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

Design Demand (DD): EDA tot * Fu * (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 lamps – 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

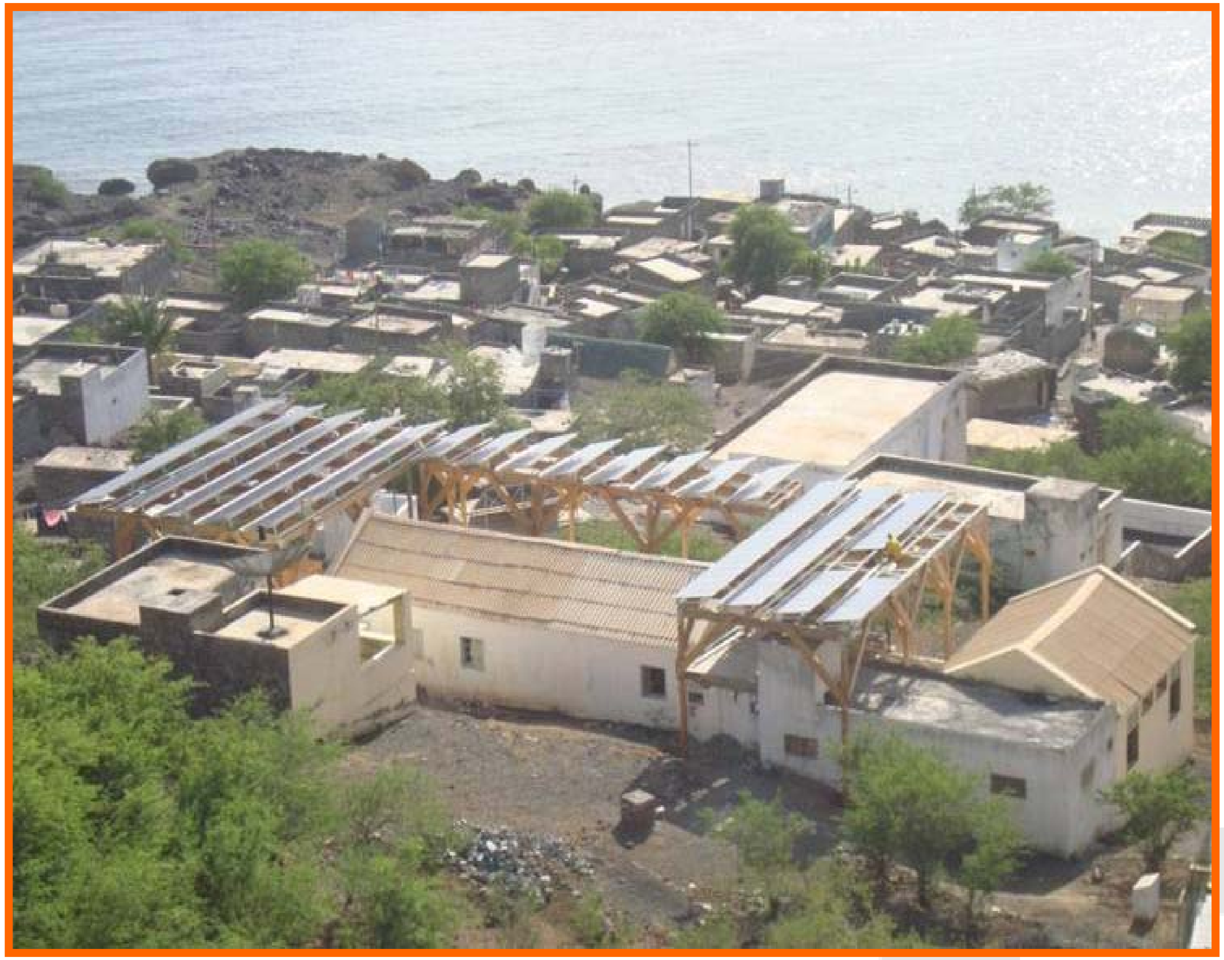
Balance between users' willingness to pay and economic sustainability

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

LEVEL	EDA (Wh)	Power Limit (kW)	Max. Energy storage capacity (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



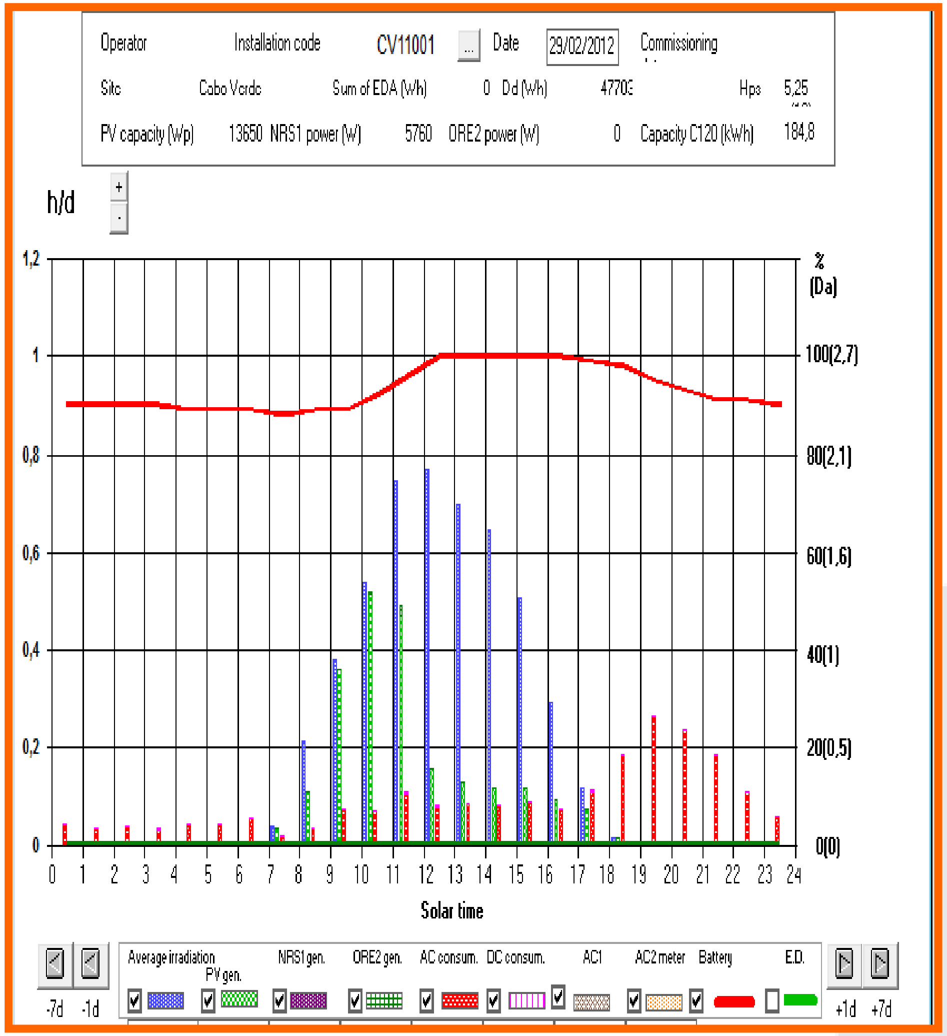
Added value solution: Engage the users

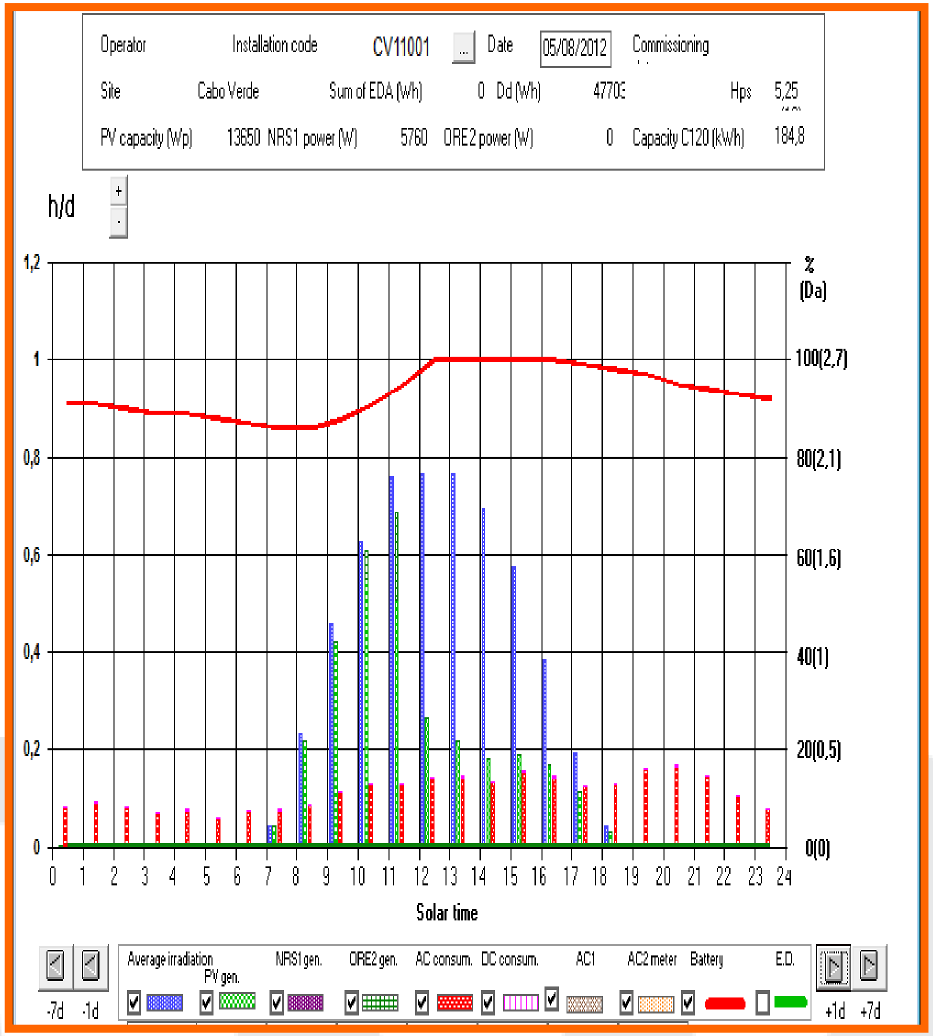
Technical solution: mechanical room

Technical solution – Single phase LV distribution

Technical solution – User interface

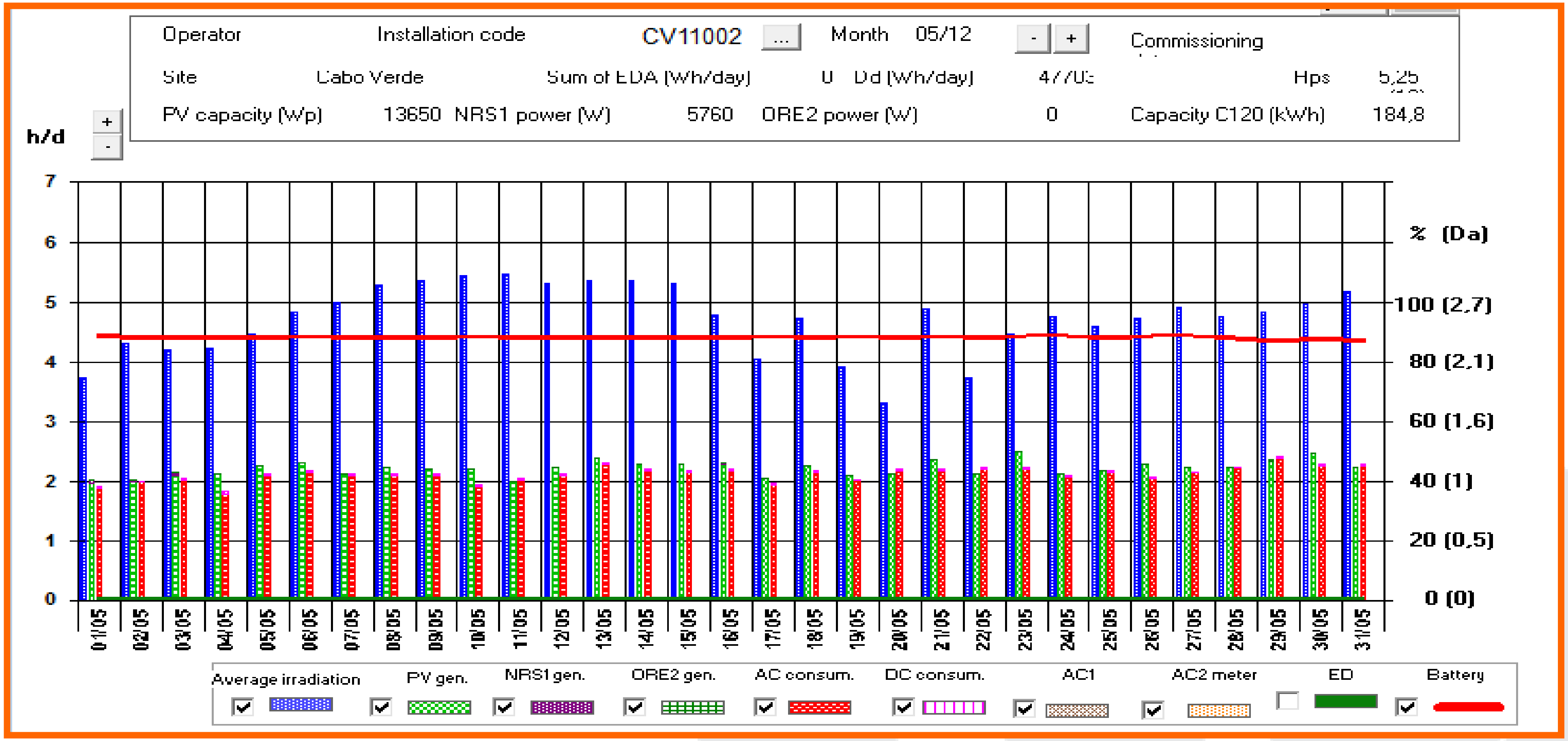
Effects of Electricity Dispenser's signal on consumer habits





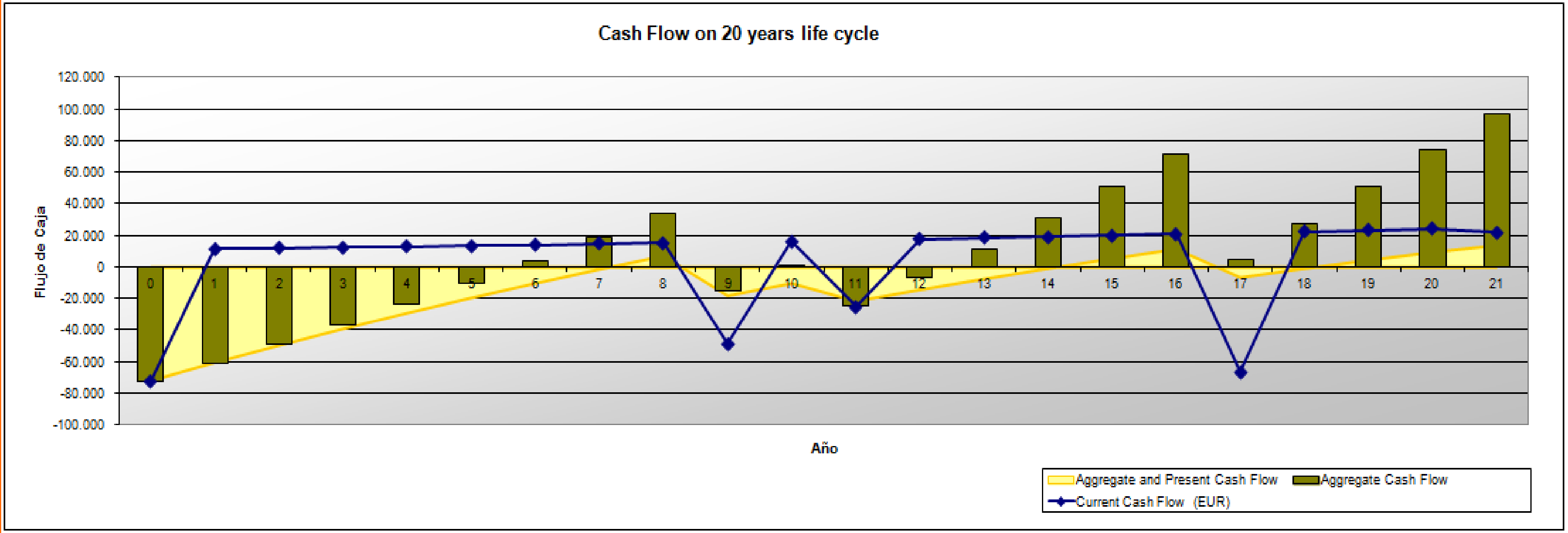
Normalized Performance indicators

- Stable daily aggregate load (red bars)
- Battery state of Charge (red line) always between 85% and 95%



Economic analysis: revenue certainty is useful for financial planning

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



NPV 13.871 EUR **Sustainable Project**

Thanks for your attention!

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